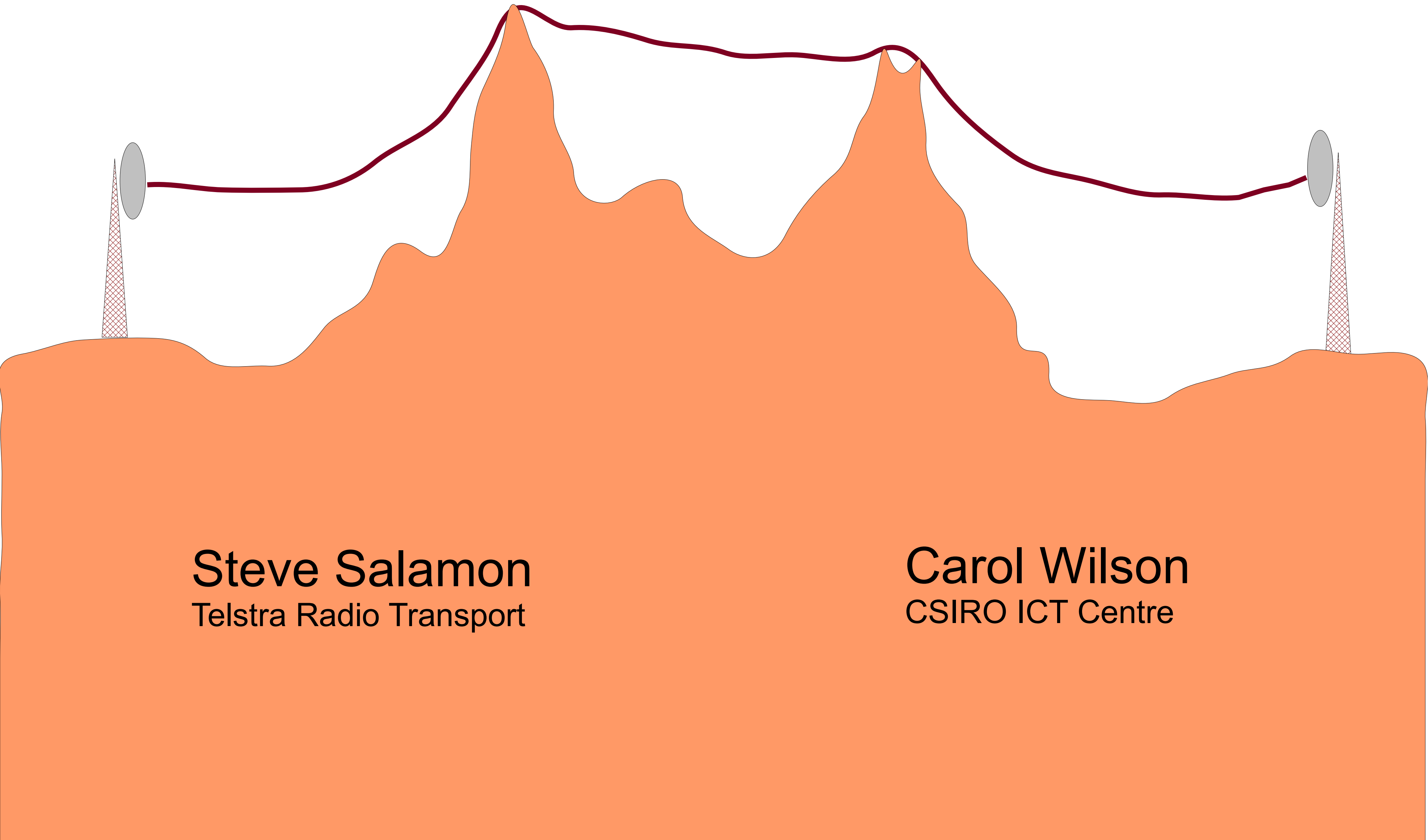
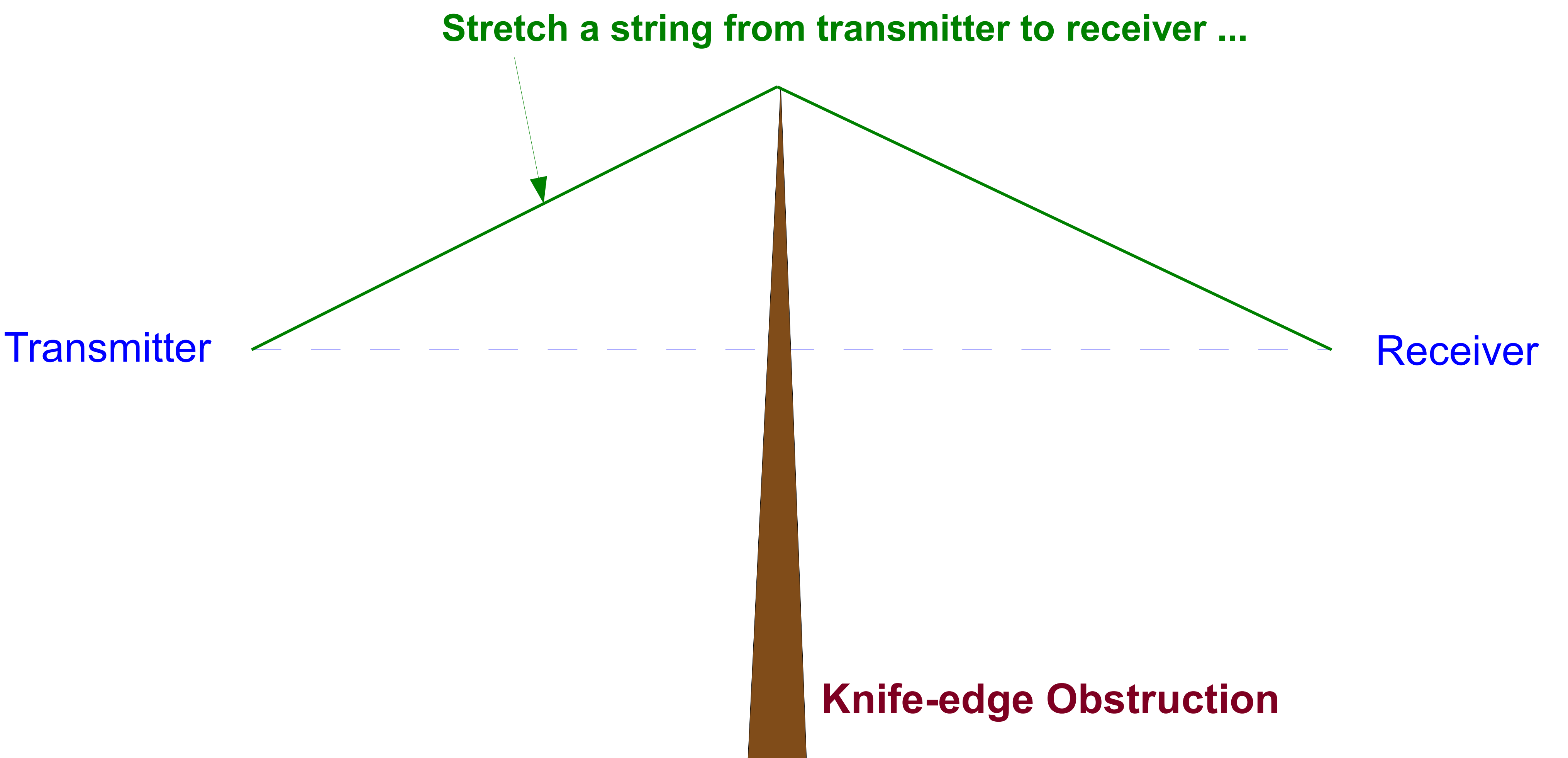
Slack-String Diffraction Model



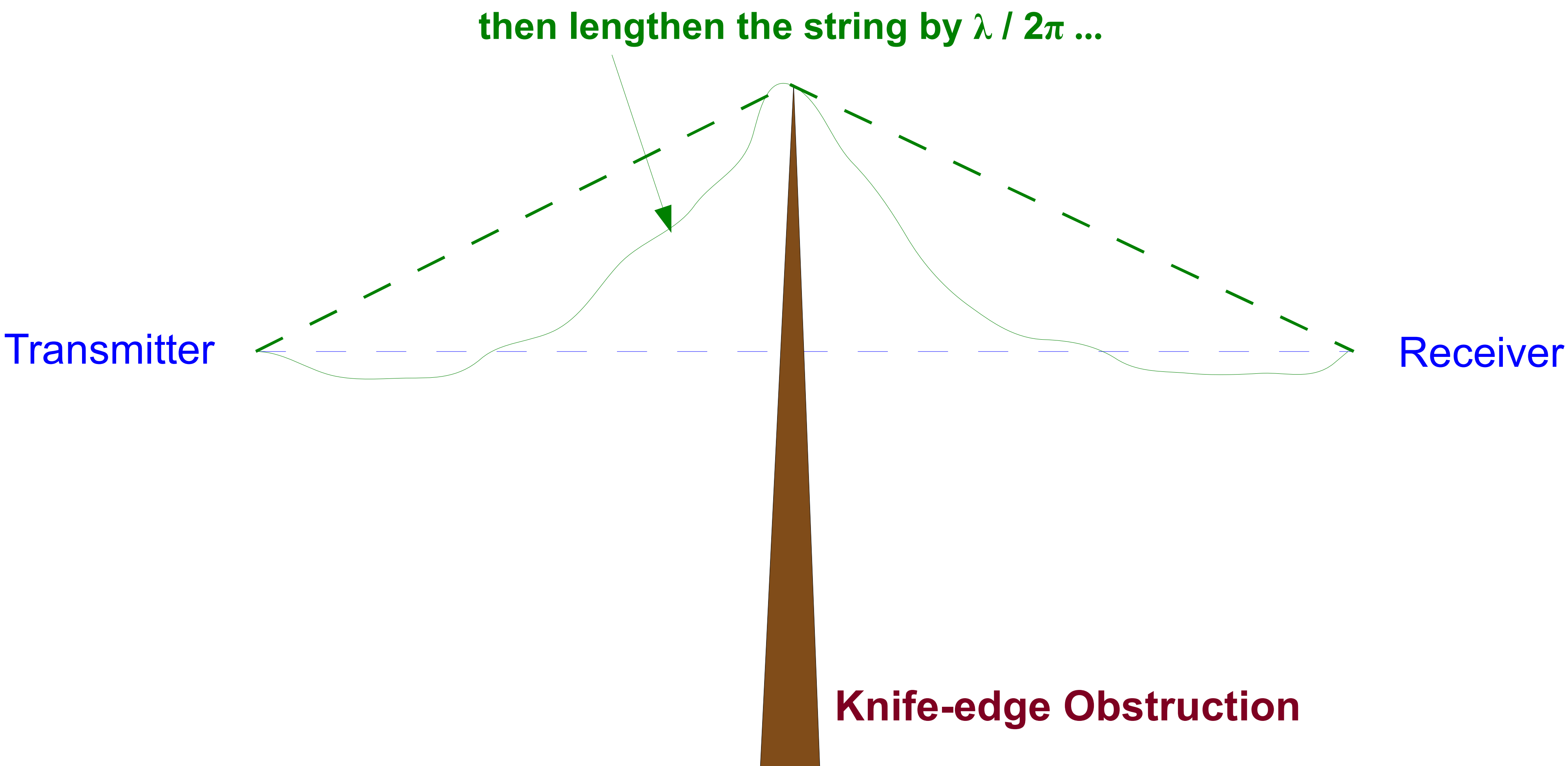
Steve Salamon
Telstra Radio Transport

Carol Wilson
CSIRO ICT Centre

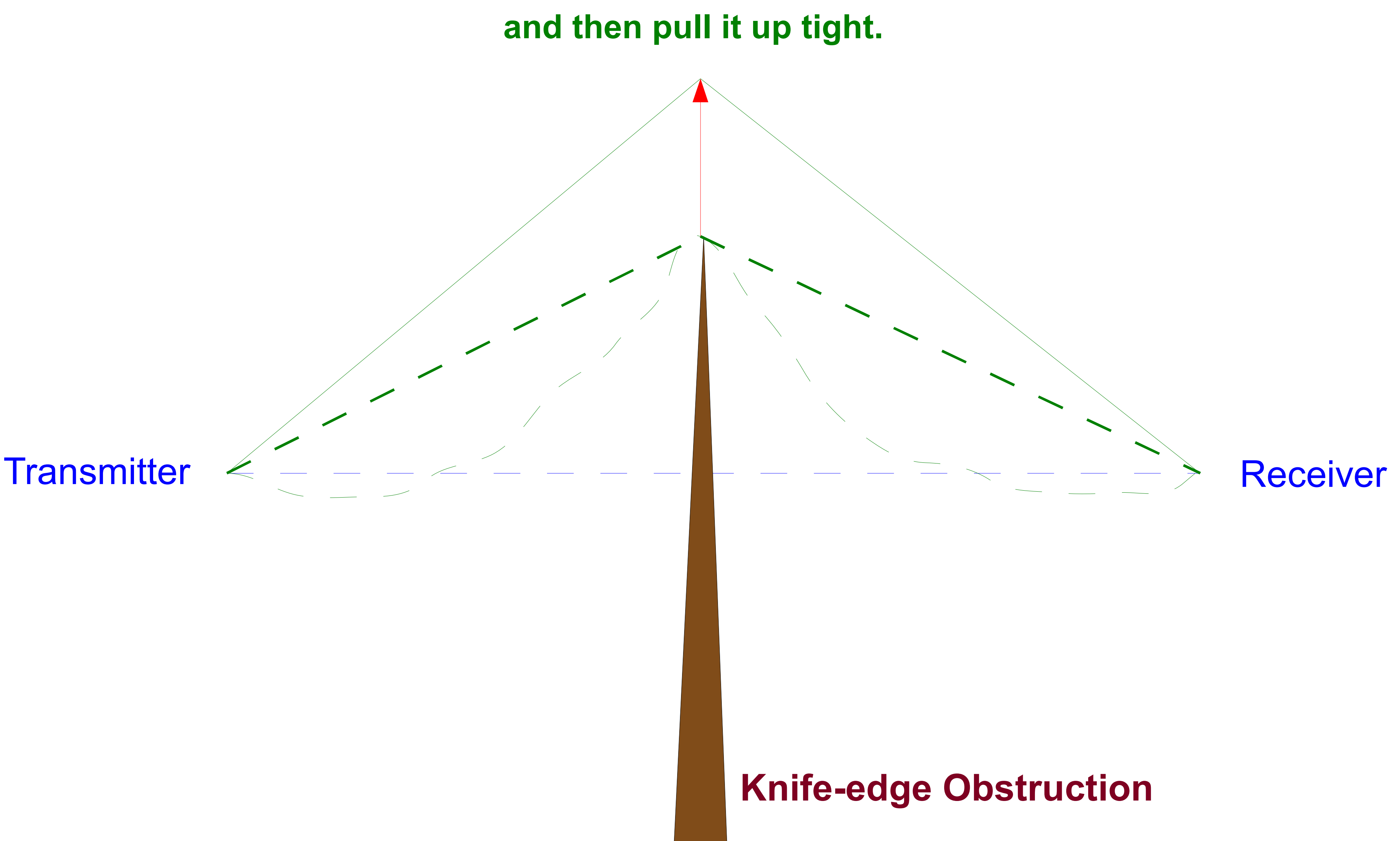
Slack-String Model – Basic Idea



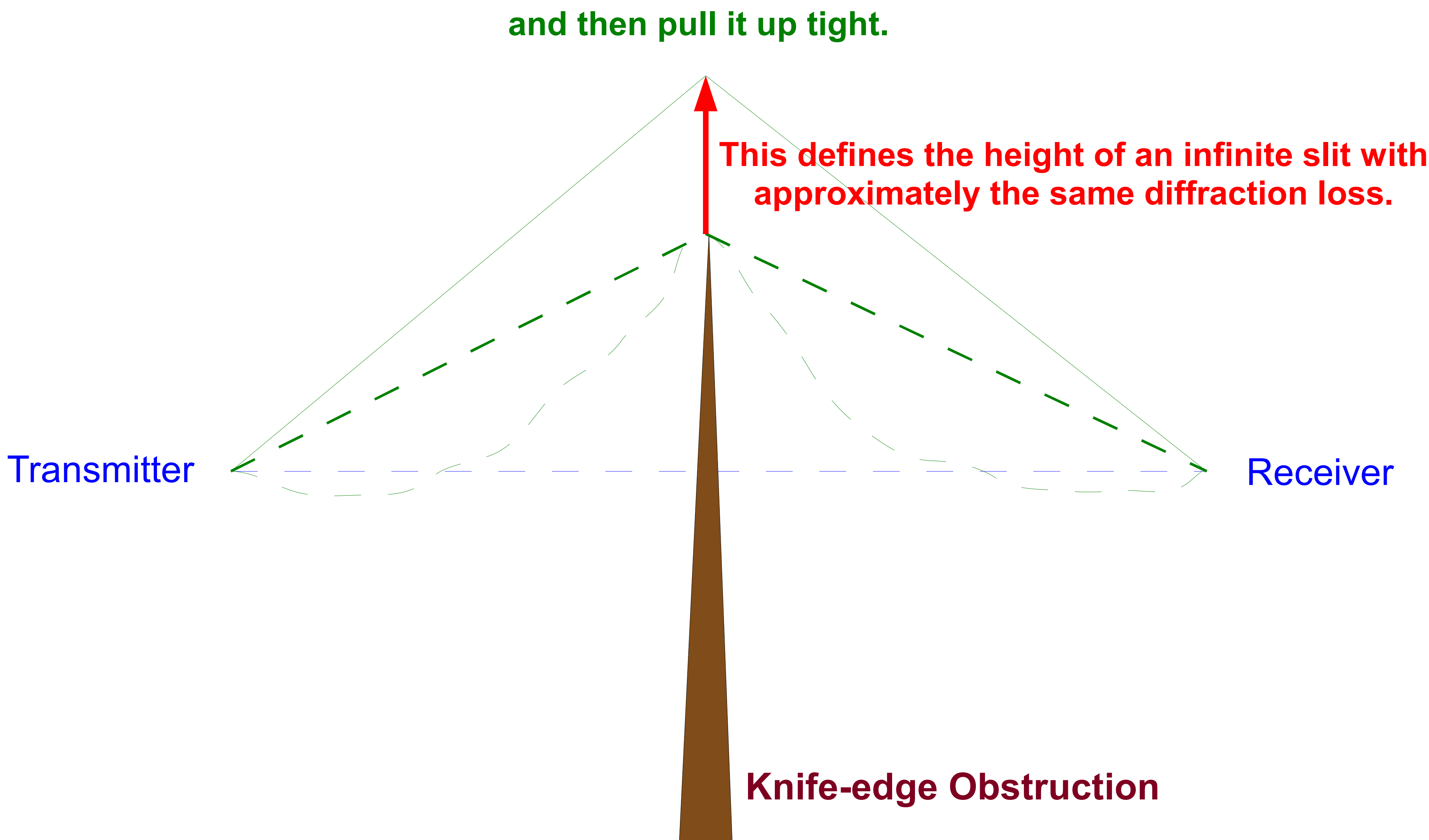
Slack-String Model – Basic Idea



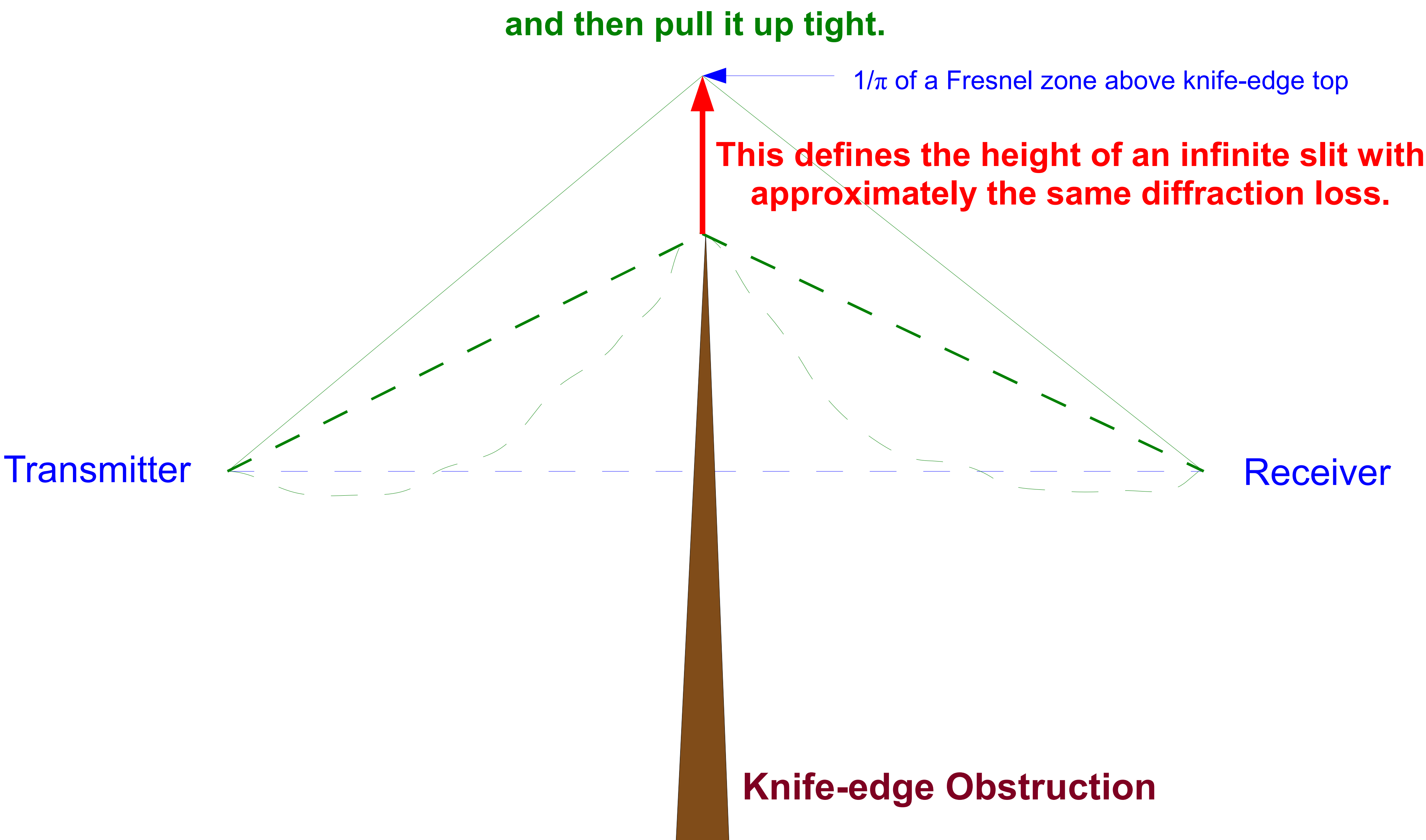
Slack-String Model – Basic Idea



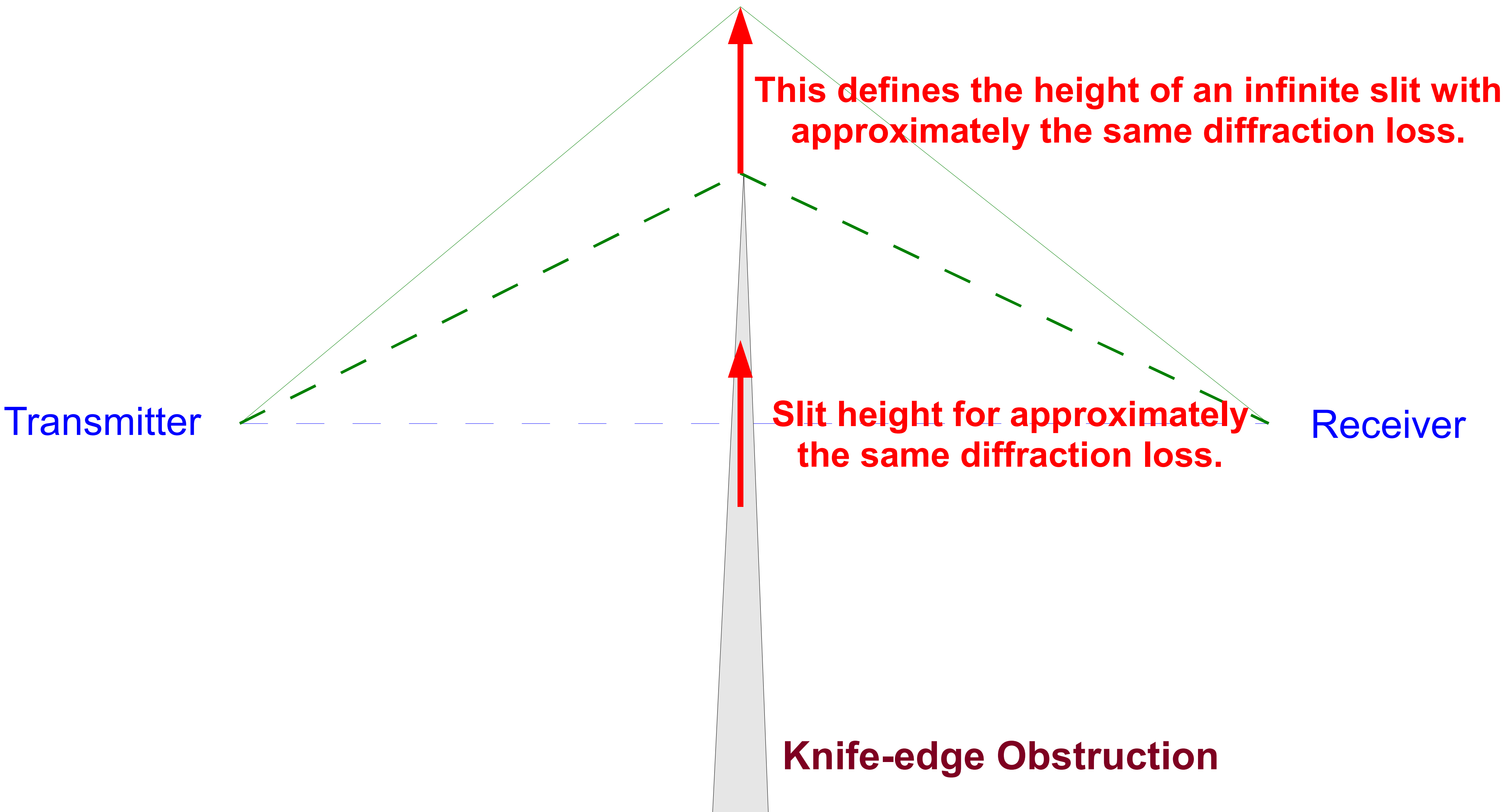
Slack-String Model – Basic Idea



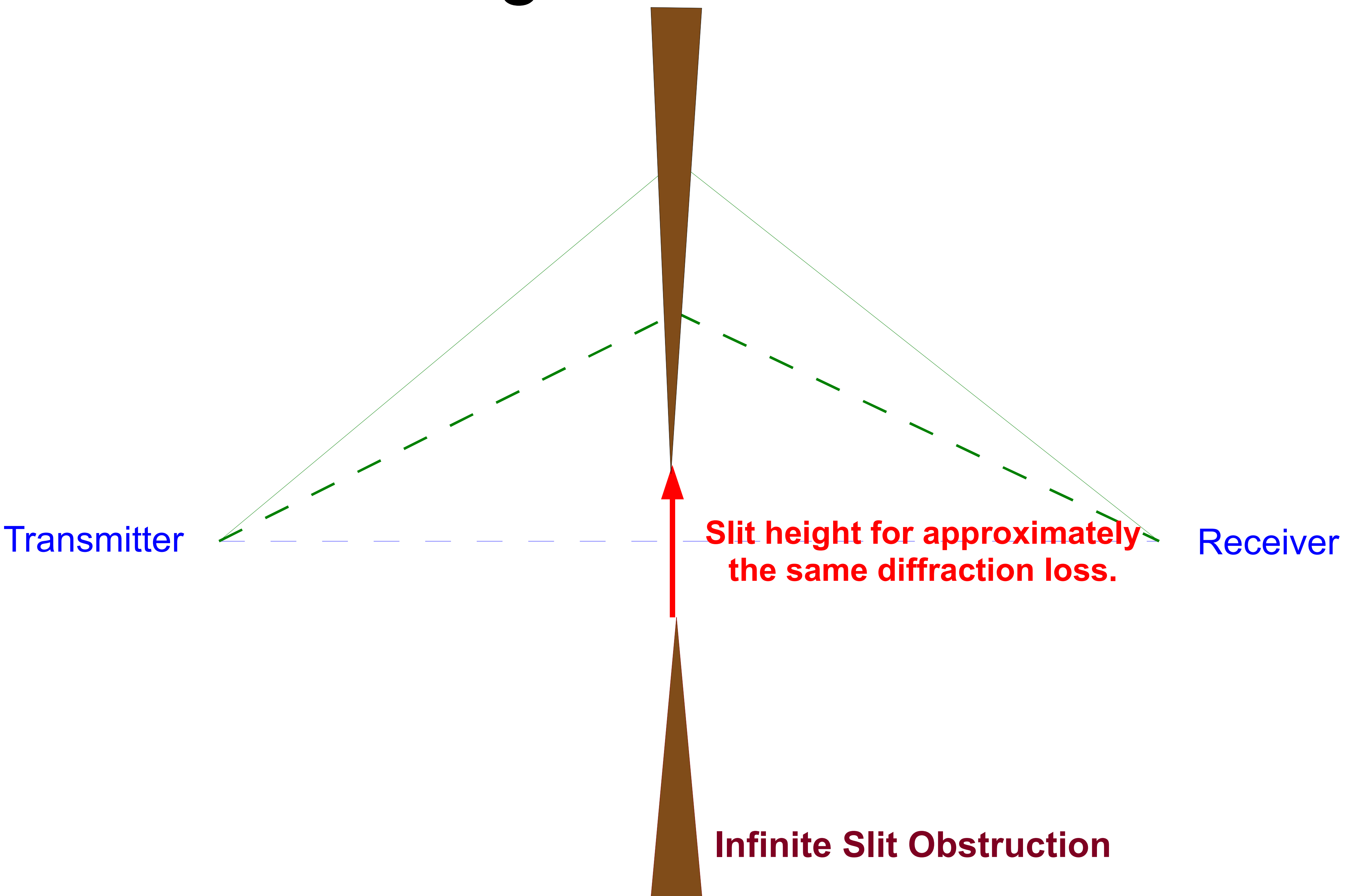
Slack-String Model – Basic Idea



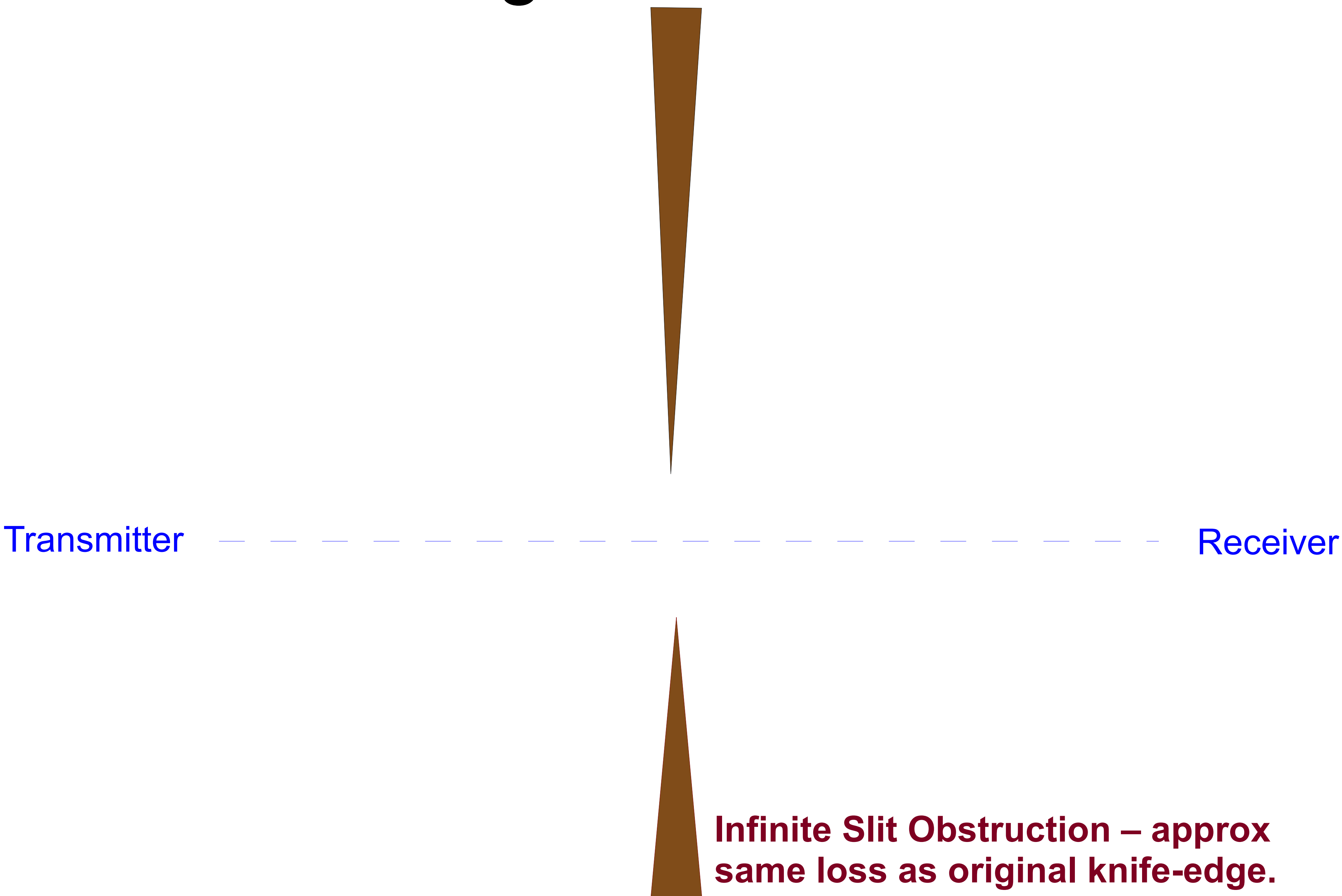
Slack-String Model – Basic Idea



Slack-String Model – Basic Idea

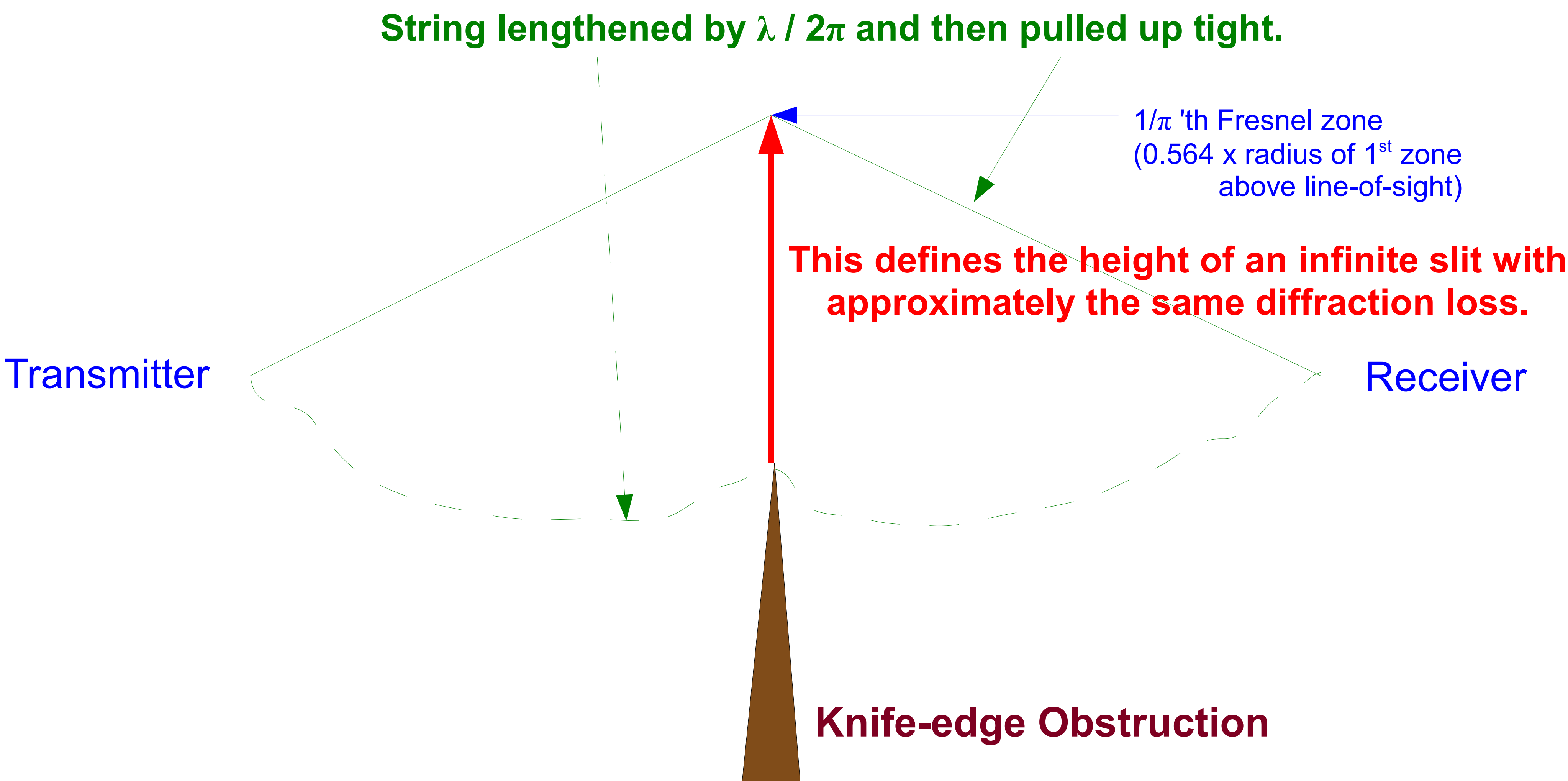


Slack-String Model – Basic Idea

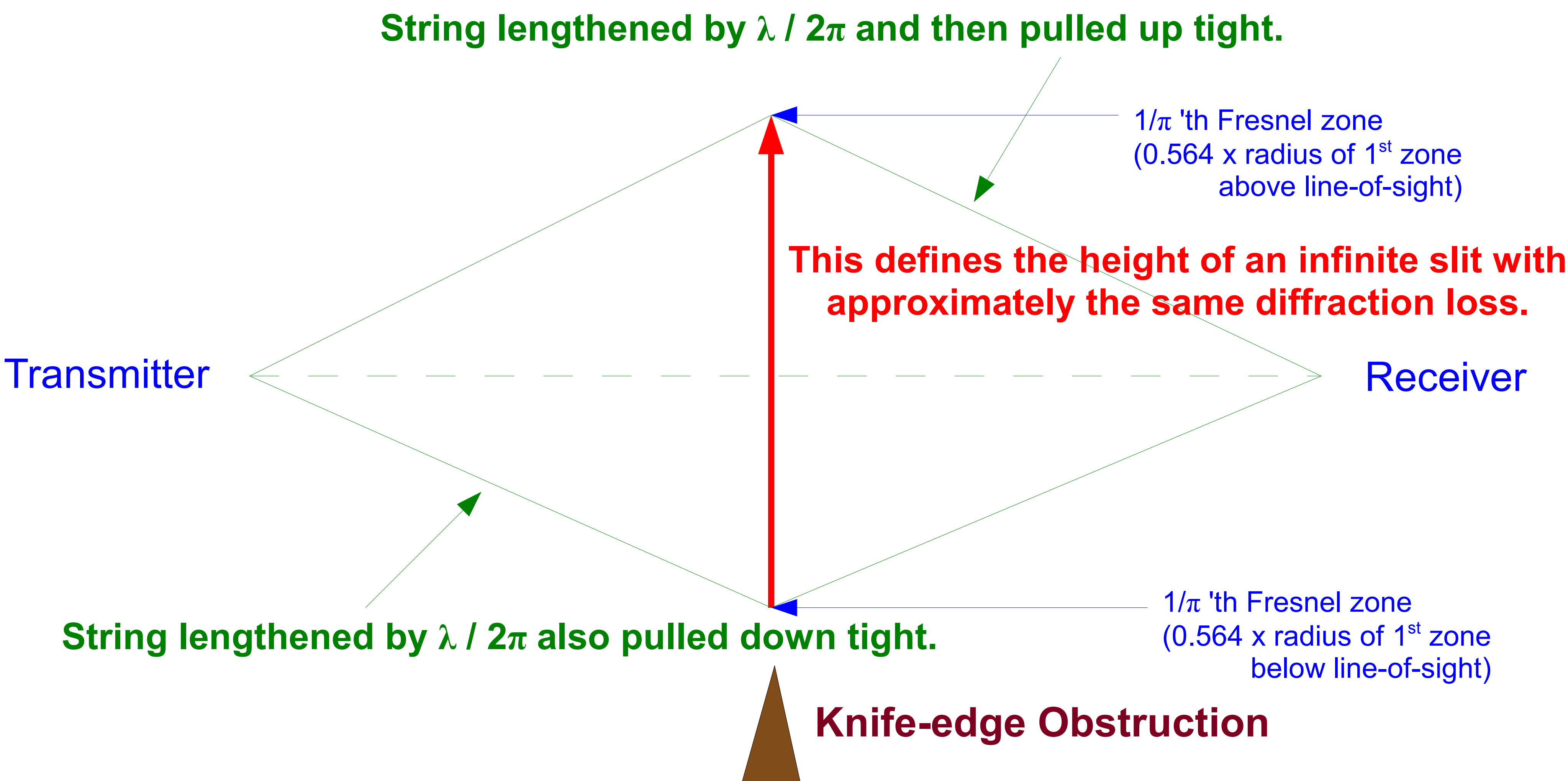


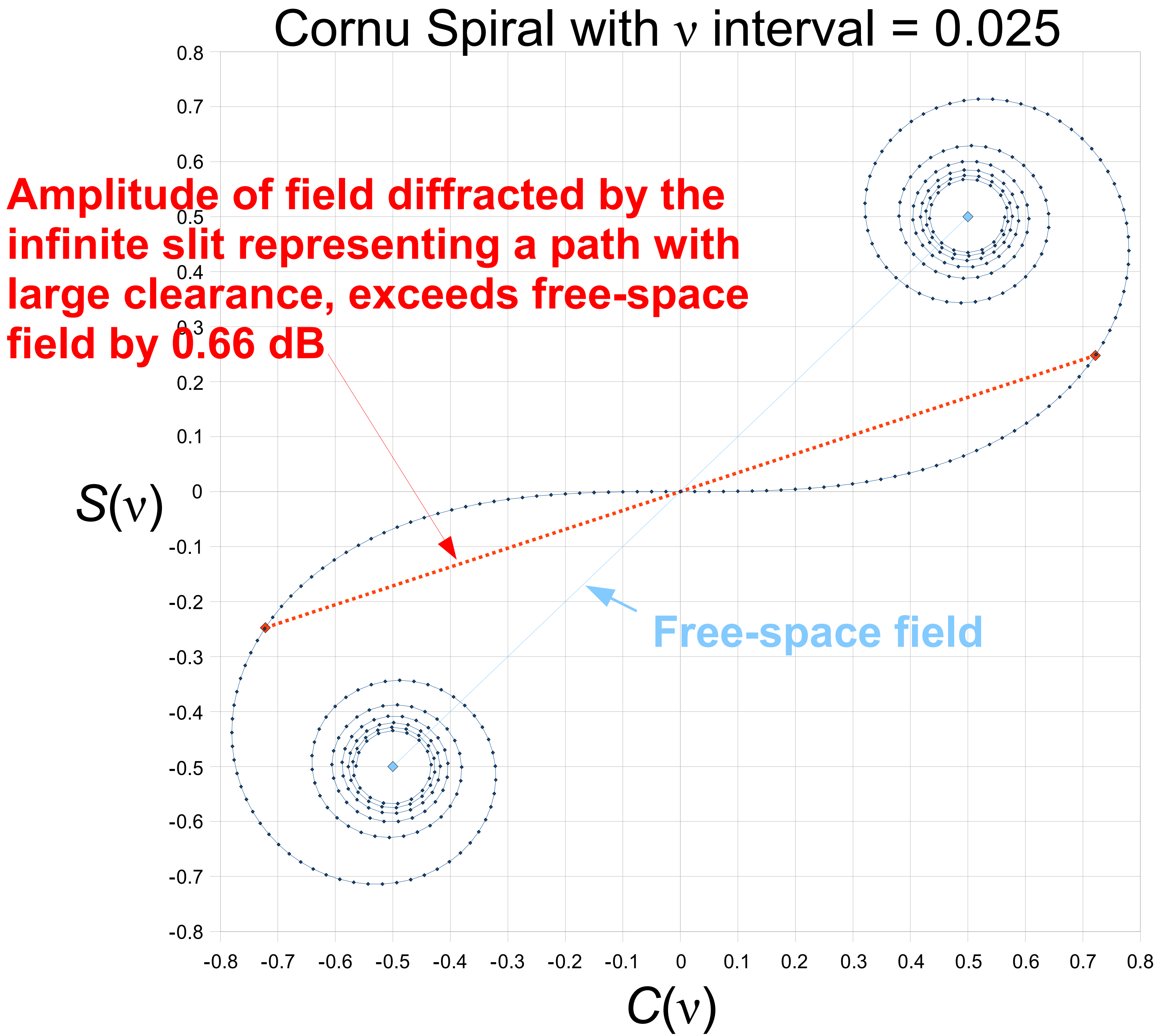
Infinite Slit Obstruction – approx same loss as original knife-edge.

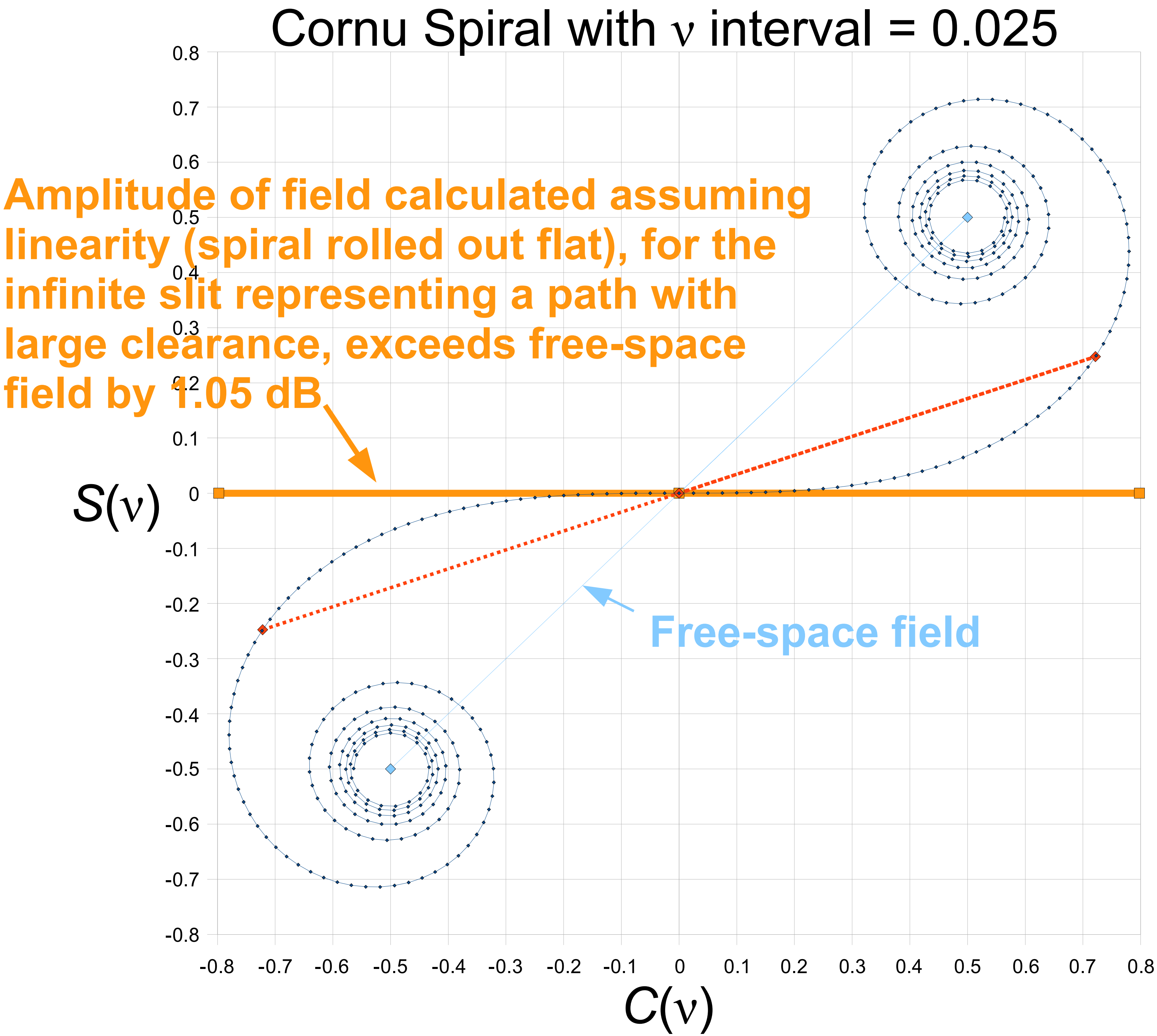
Slack-String Model with Clear Line-of-sight (small clearance)



Slack-String Model with Clear Line-of-sight (large clearance)




Cornu Spiral with ν interval = 0.025
Amplitude of field diffracted by the infinite slit representing a path with large clearance, exceeds free-space field by 0.66 dB
Free-space field
S(ν)
C(ν)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8



Cornu Spiral with ν interval = 0.025
Amplitude of field calculated assuming linearity (spiral rolled out flat), for the infinite slit representing a path with large clearance, exceeds free-space field by 1.05 dB
Free-space field
S(ν)
C(ν)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Correction of 1.05 dB over-prediction of field-strength for un-obstructed and grazing line-of-sight knife-edge paths

Equation (12):

$$L = 20\log\left(\frac{R_1}{h_s}\right) + \left[10\log\left(\frac{4}{\pi}\right)\right].\max\left\{\min\left[\frac{h_s}{0.28R_1} - 1, 1\right], 0\right\}$$

Linear model [equ. (8)]
i.e. Cornu Spiral
rolled out flat

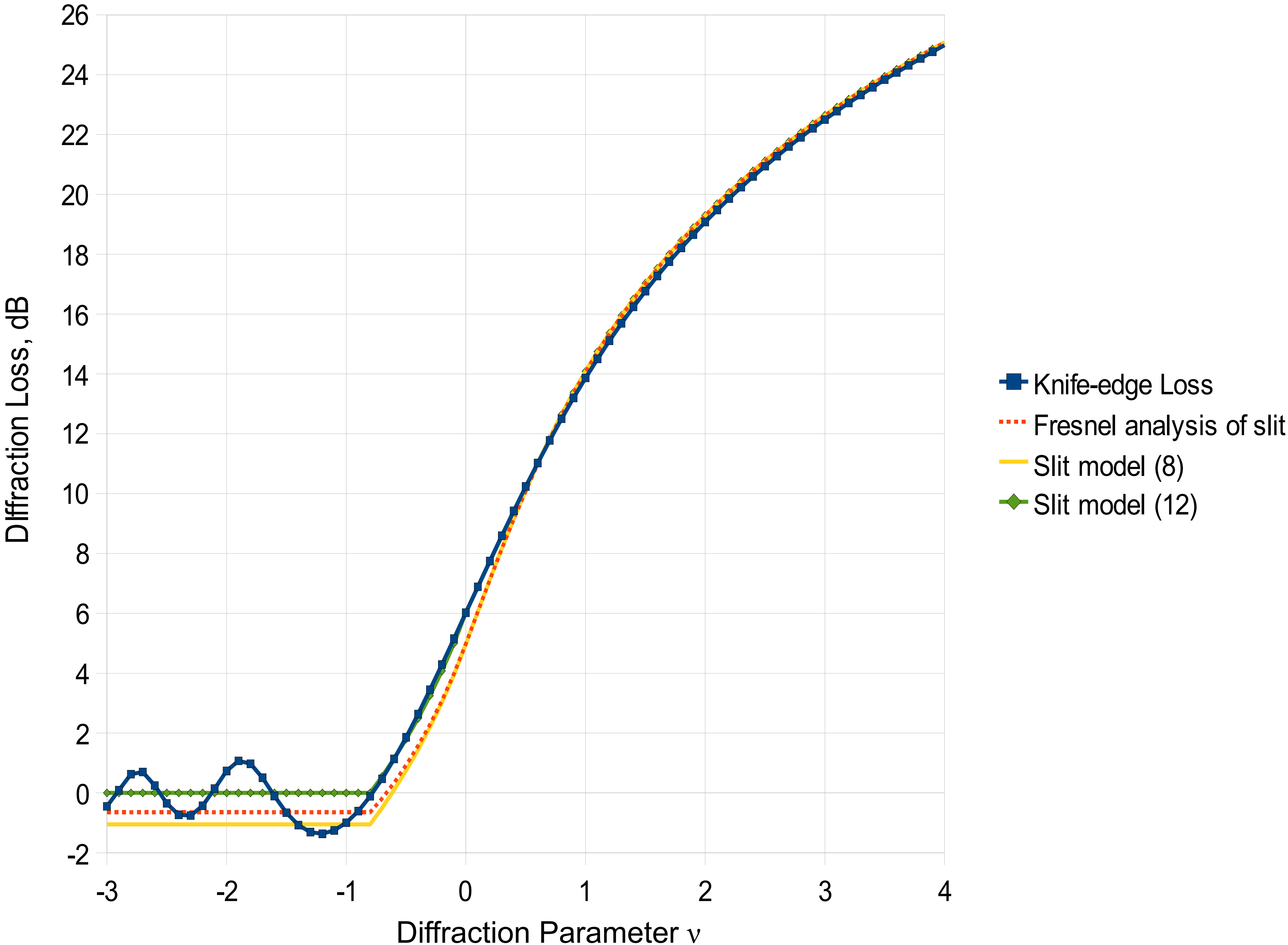
Correction factor adds 1.05 dB to the calculated loss for ν ≤ 0.006

Correction of 1.05 dB over-prediction of field-strength for un-obstructed and grazing line-of-sight knife-edge paths

Equation (12):

$$L = 20\log\left(\frac{R_1}{h_s}\right) + \left[10\log\left(\frac{4}{\pi}\right)\right].\max\left\{\min\left[\frac{h_s}{0.28R_1} - 1, 1\right], 0\right\}$$

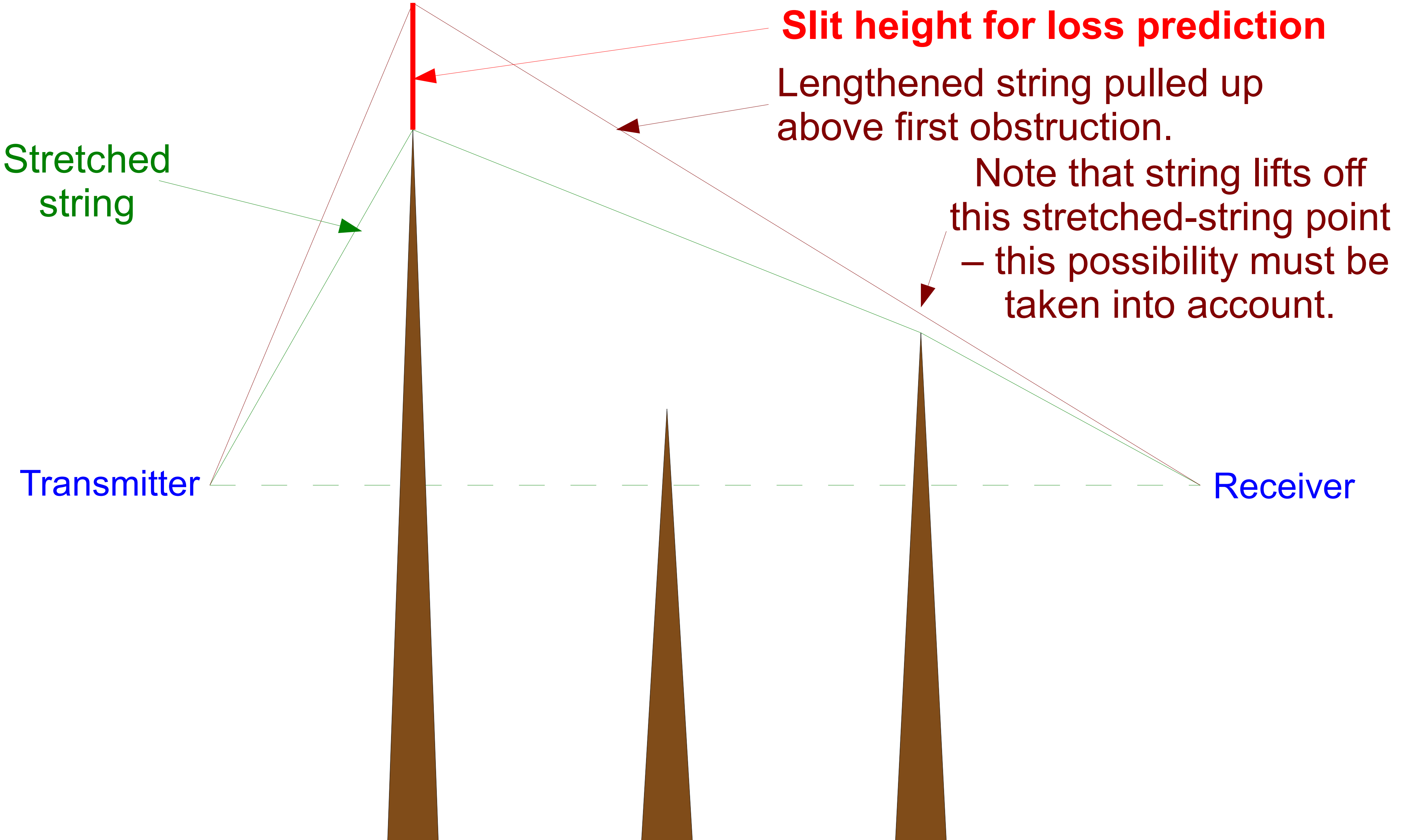
Accuracy: within 0.3 dB for ν ≥ -0.83; otherwise within 1.2 dB



26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
DIffraction Loss, dB
-3
-2
-1
0
1
2
3
4
Diffraction Parameter ν
Knife-edge Loss
Fresnel analysis of slit
Slit model (8)
Slit model (12)

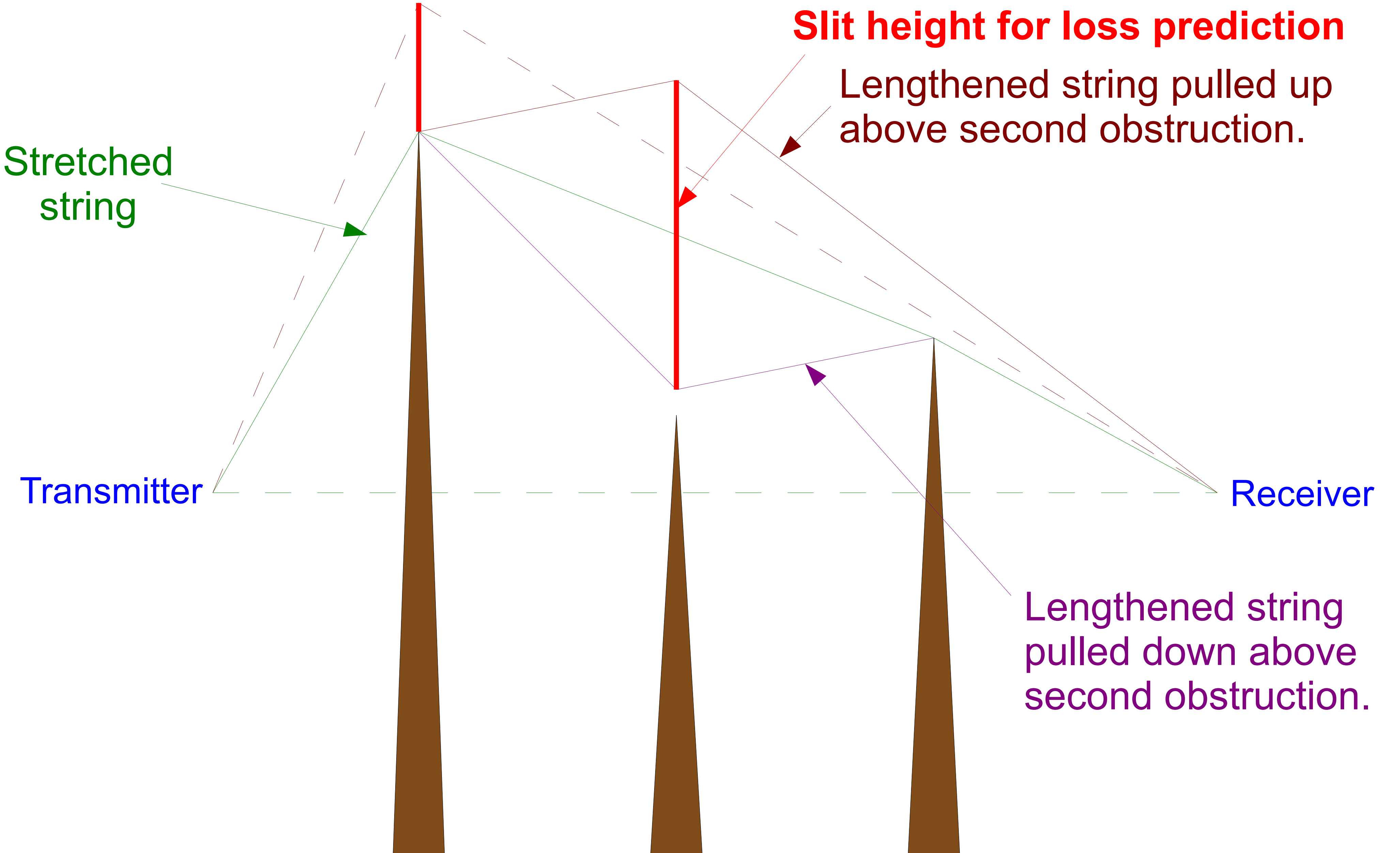
Extension to Multiple Knife-edges

Increase length of string by $\lambda/2\pi$ and pull up and down as far as possible above each obstruction in turn, to define equivalent slit height.



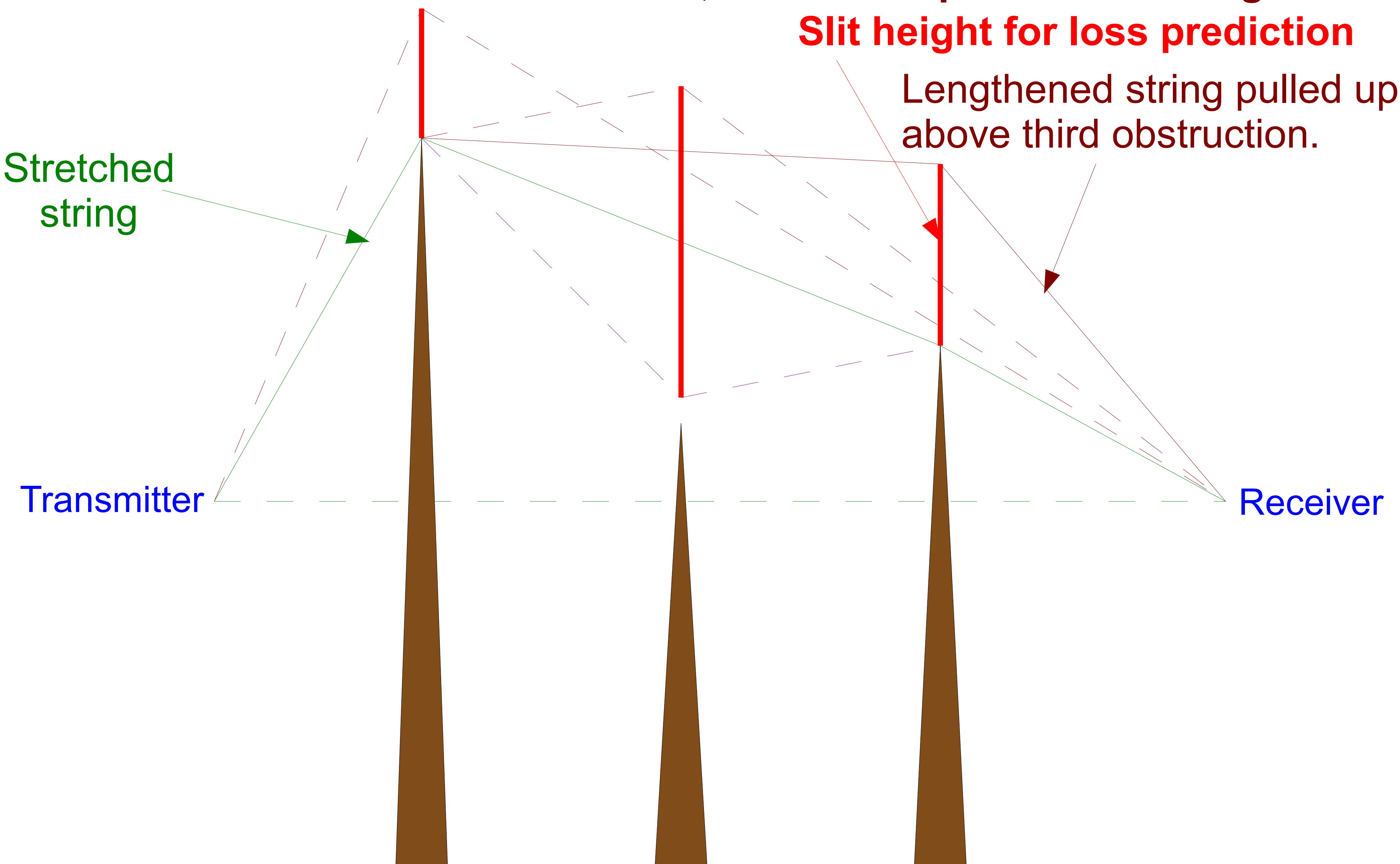
Extension to Multiple Knife-edges

Increase length of string by $\lambda/2\pi$ and pull up and down as far as possible above each obstruction in turn, to define equivalent slit height.



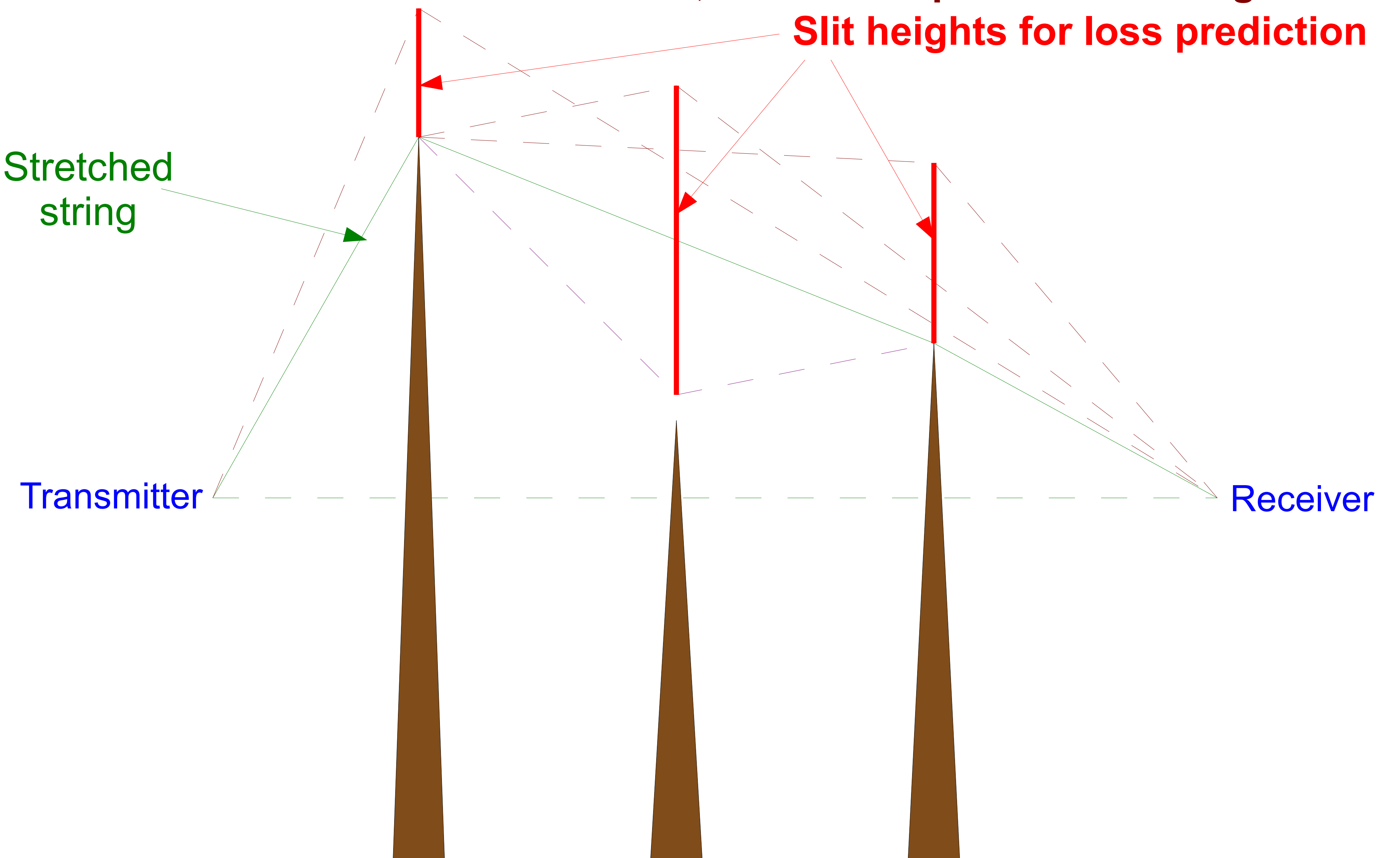
Extension to Multiple Knife-edges

Increase length of string by $\lambda/2\pi$ and pull up and down as far as possible above each obstruction in turn, to define equivalent slit height.



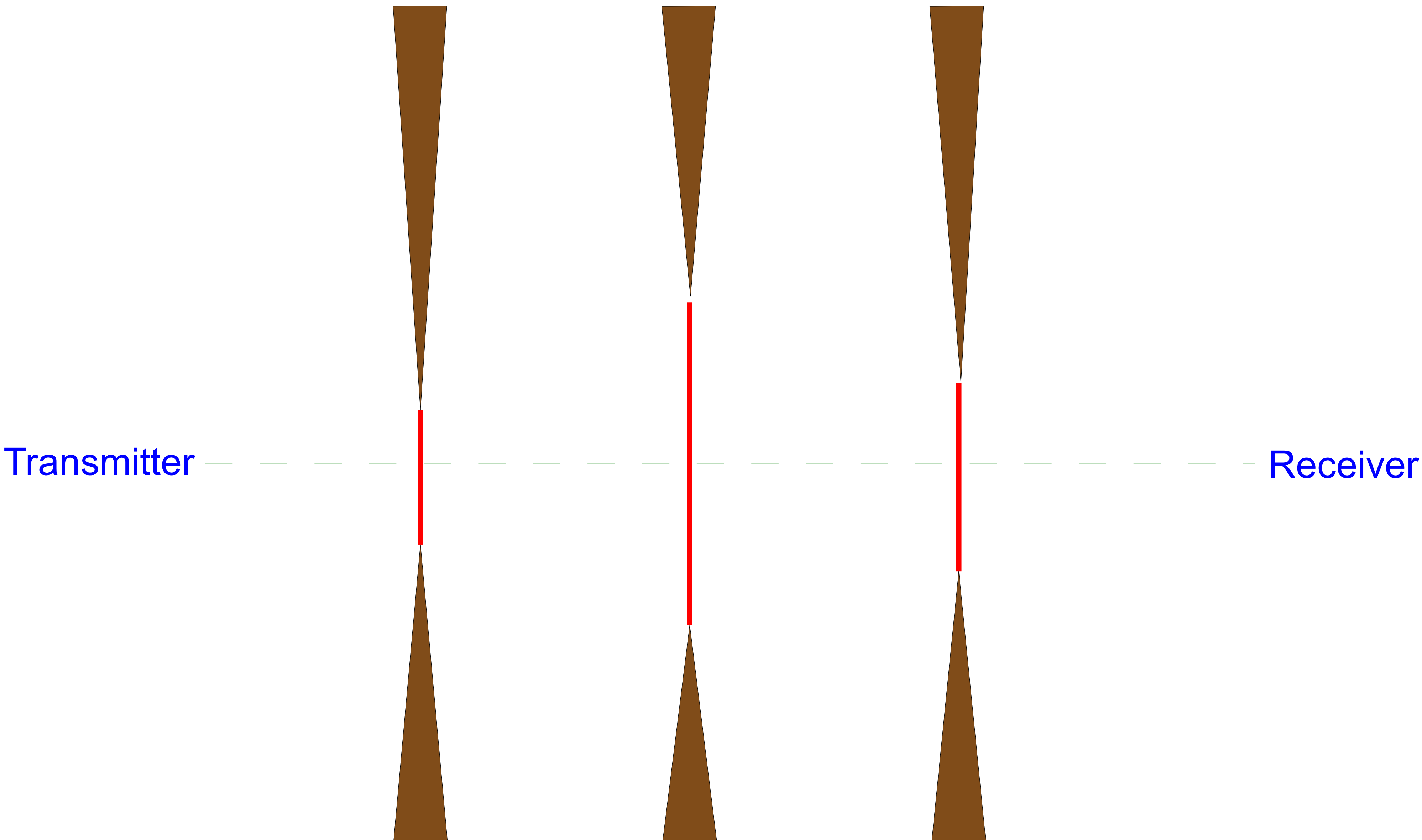
Extension to Multiple Knife-edges

Increase length of string by $\lambda/2\pi$ and pull up and down as far as possible above each obstruction in turn, to define equivalent slit height.



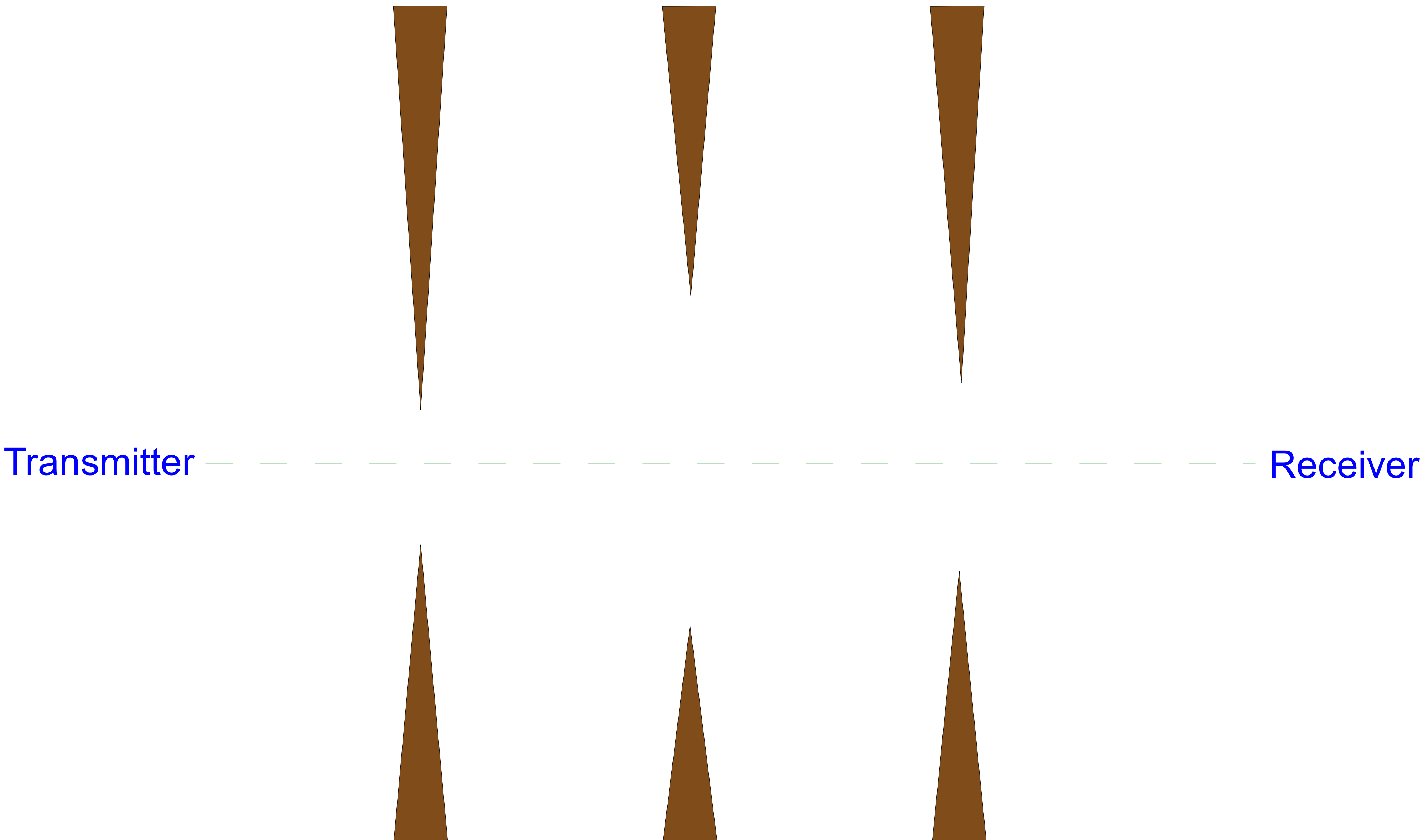
Extension to Multiple Knife-edges

Estimation of loss by analysis of equivalent multiple slit problem.



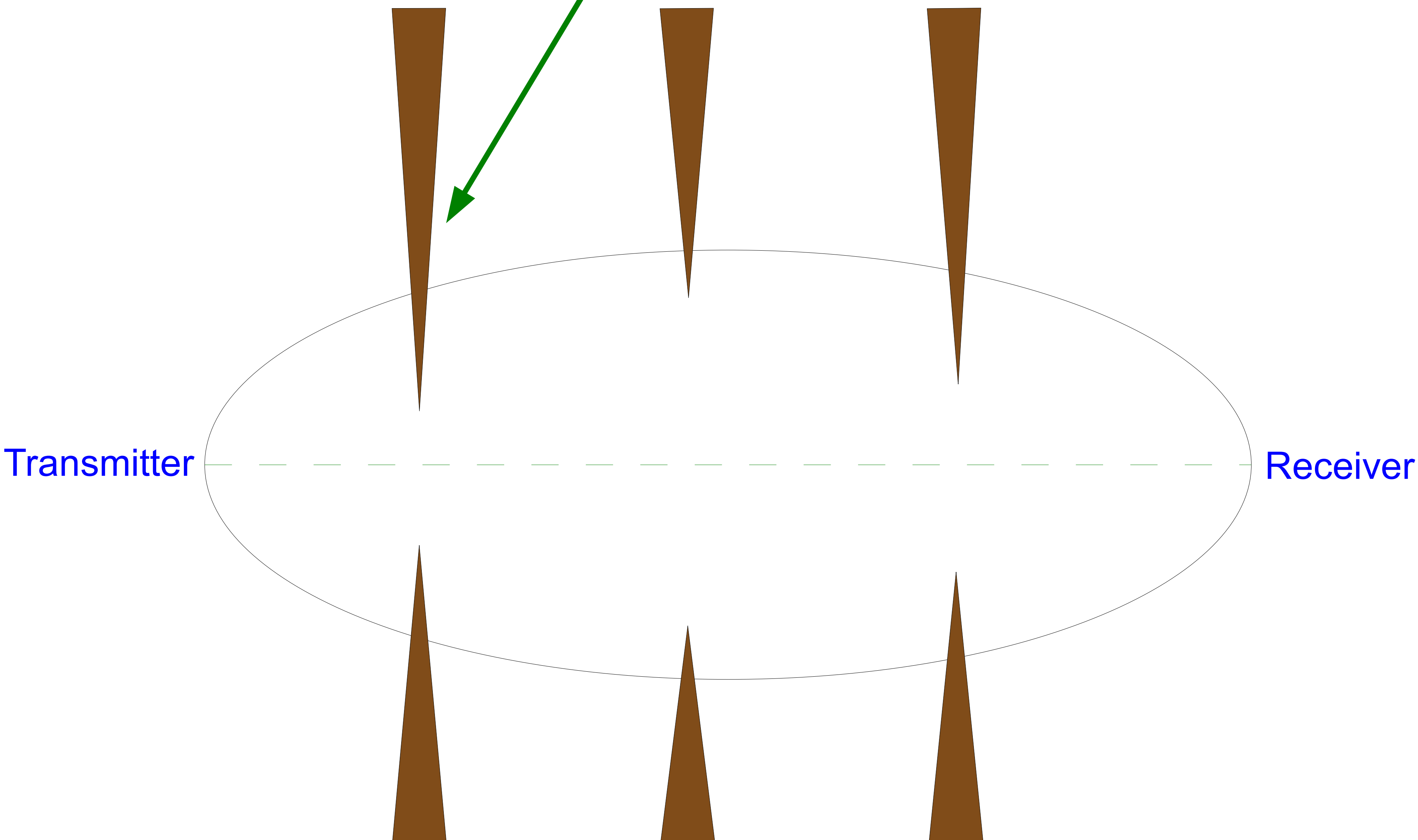
Extension to Multiple Knife-edges

Estimation of loss by analysis of equivalent multiple slit problem.



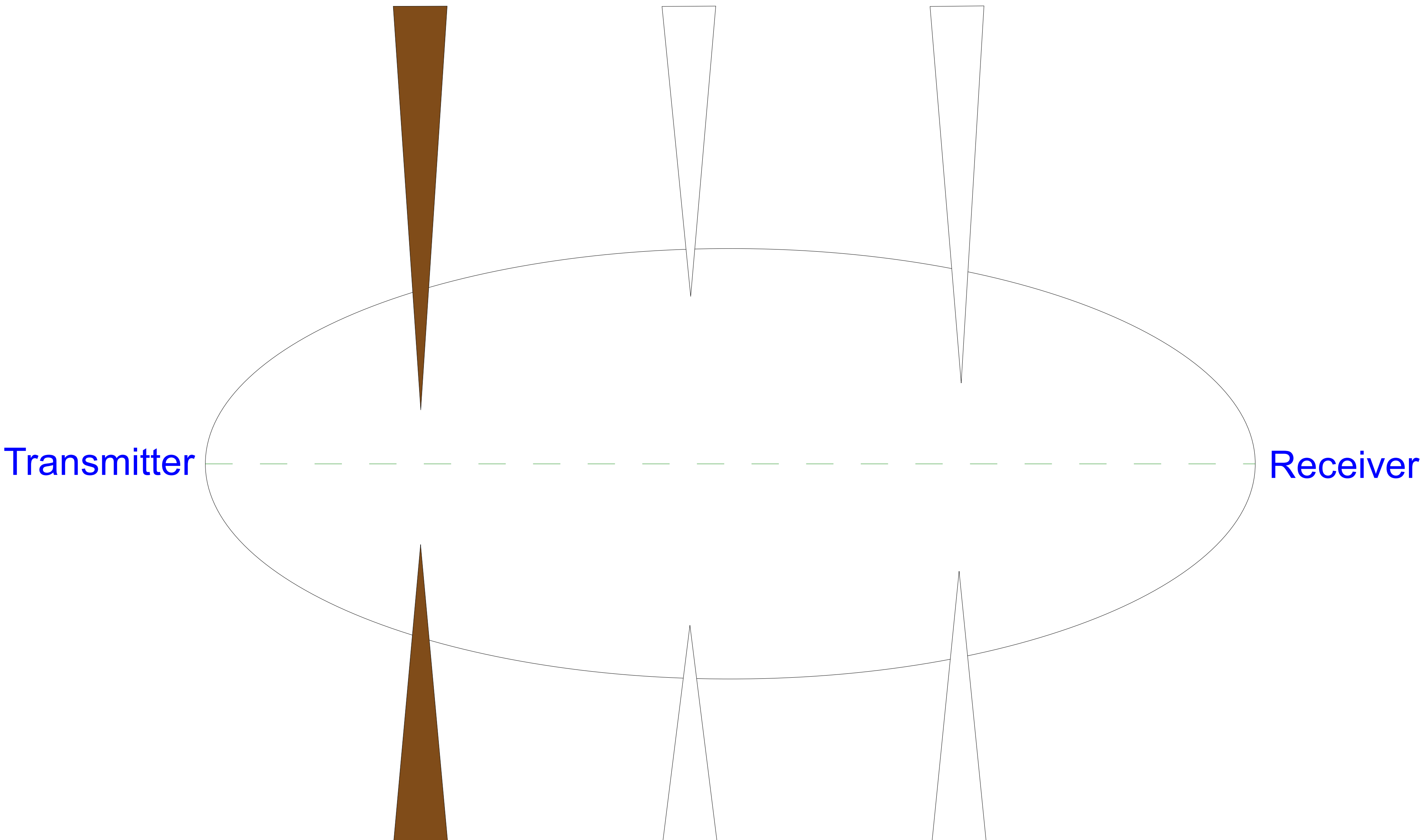
Multiple Slit Diffraction

Follow similar process to Deygout multiple knife-edge – identify obstruction with greatest loss



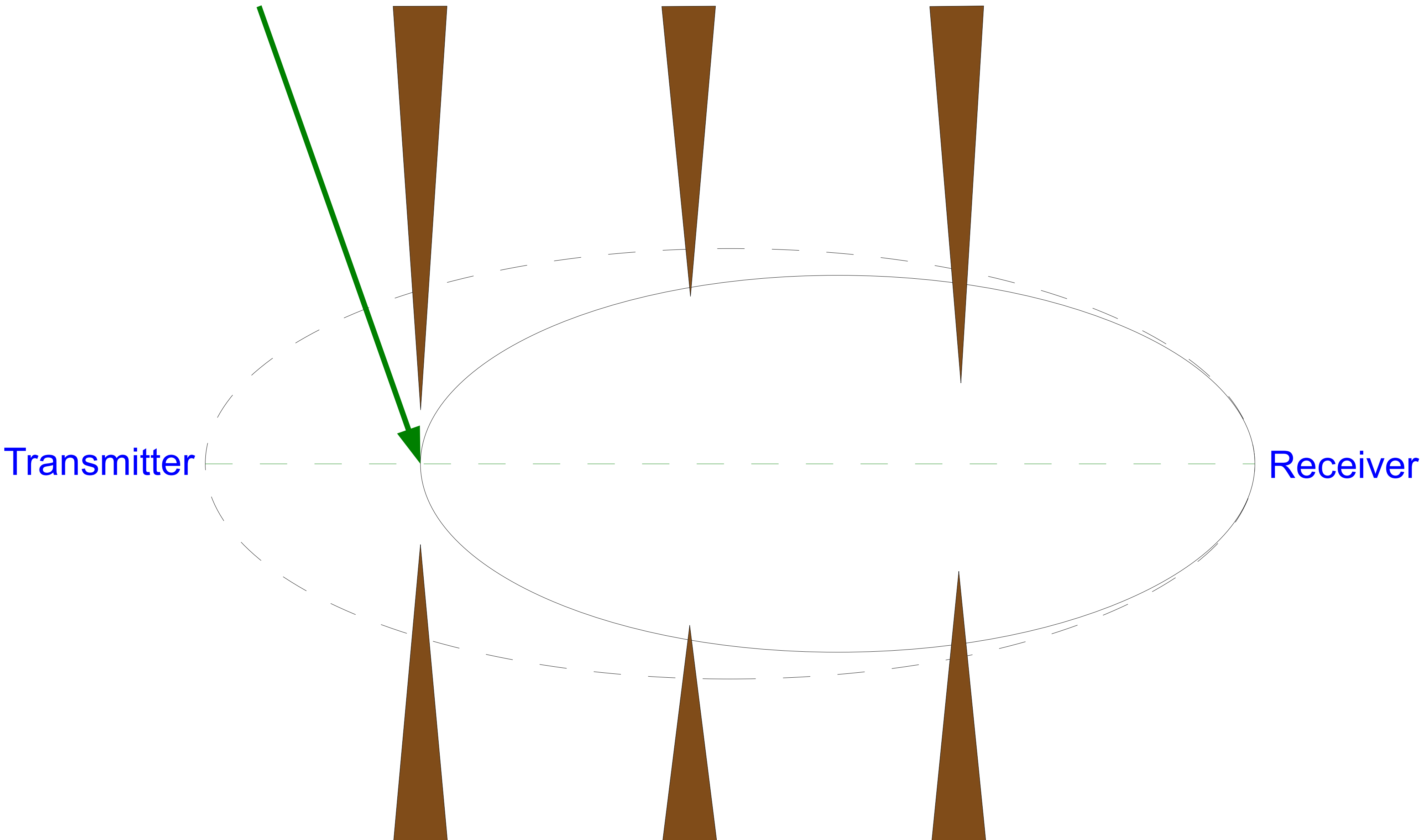
Multiple Slit Diffraction

Follow similar process to Deygout multiple knife-edge – identify obstruction with greatest loss and evaluate it first, ignoring the influence of the other obstructions.

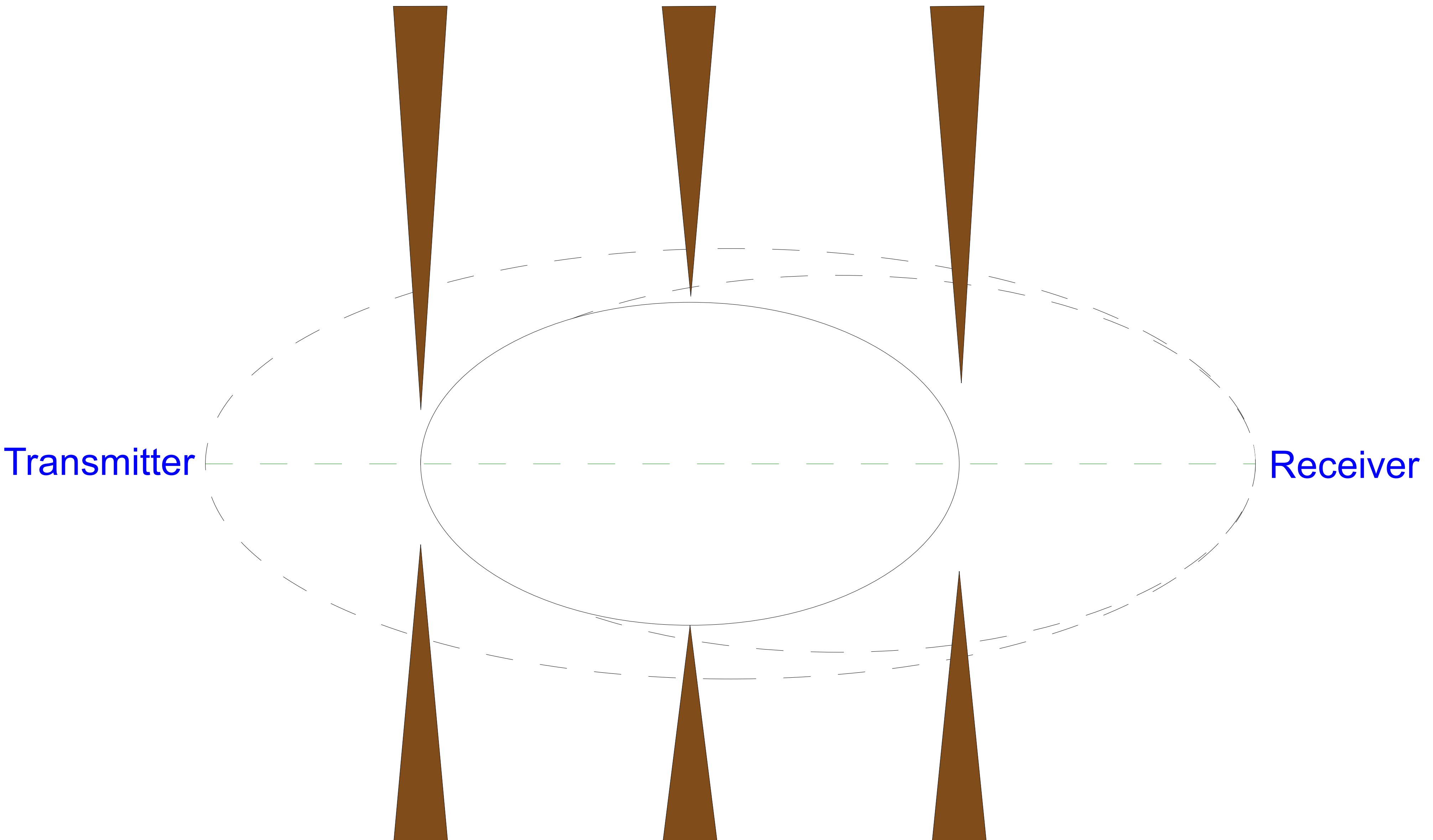


Multiple Slit Diffraction

Then repeat the process for remaining sub-path(s), using the obstruction just evaluated as an effective source point.



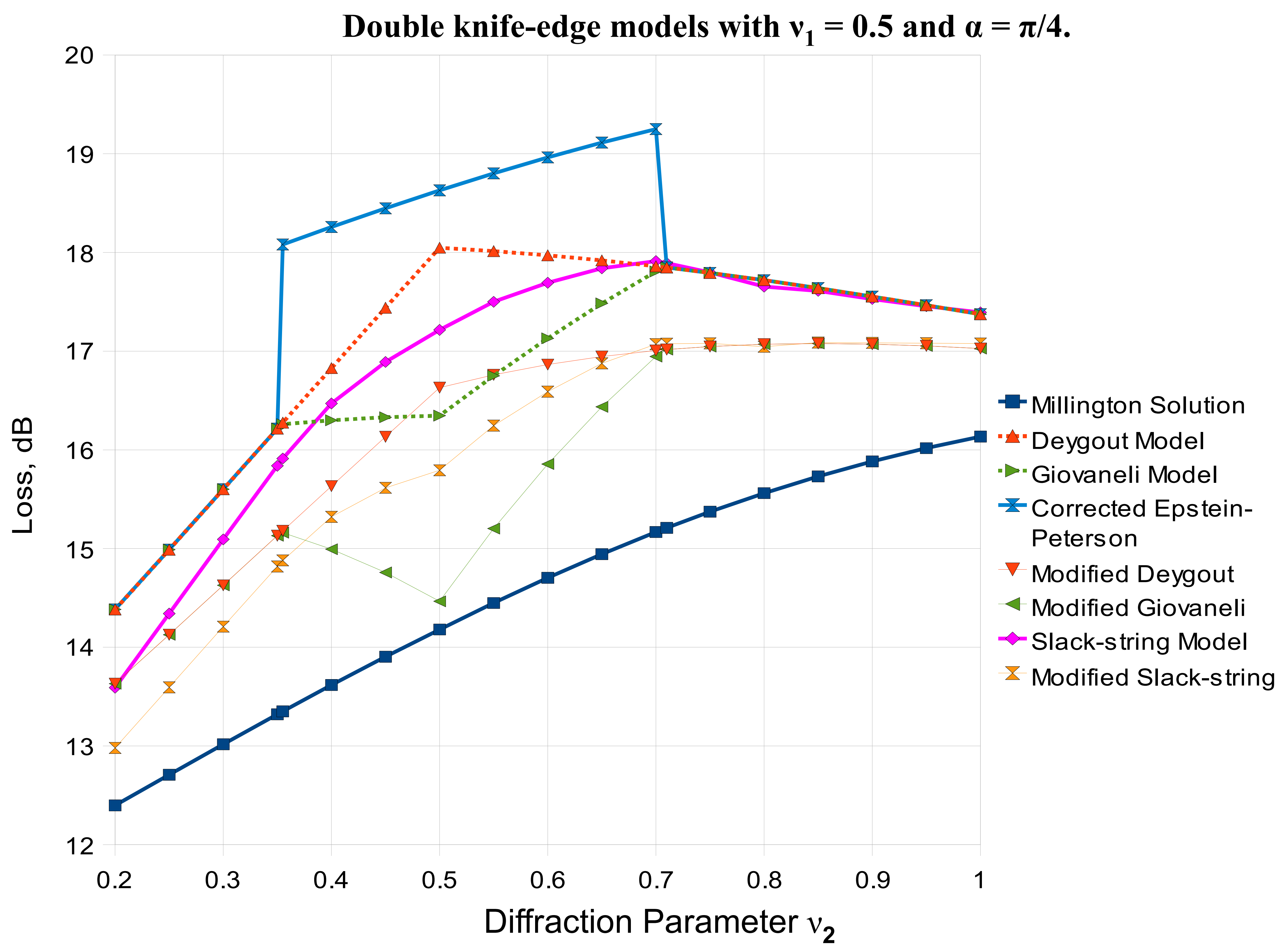
Multiple Slit Diffraction



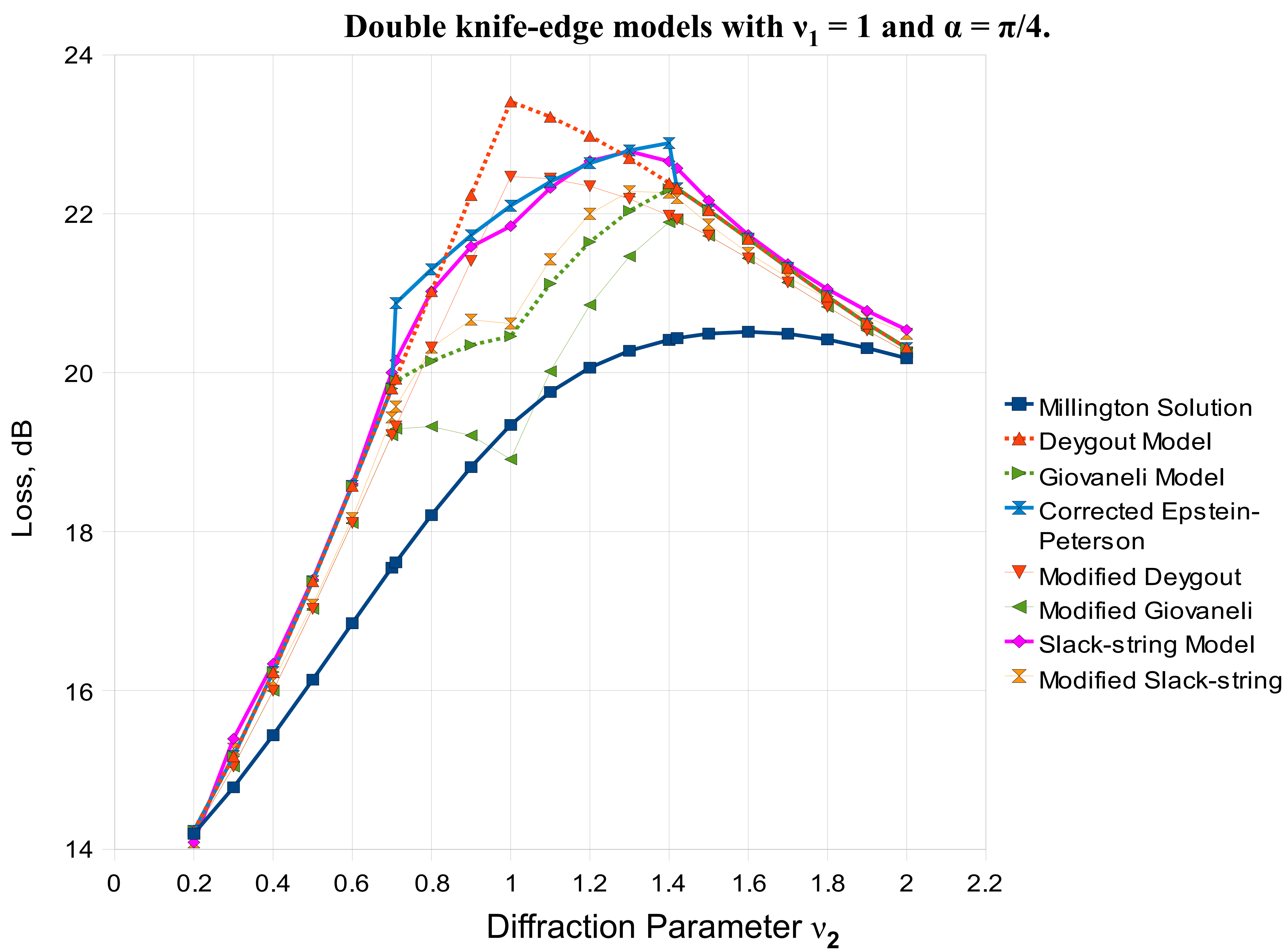
Error of models compared to Millington double knife-edge solution for 164 trials with $0 \le \nu \le 4$ and 1 degree $\le \alpha \le$ 89 degrees

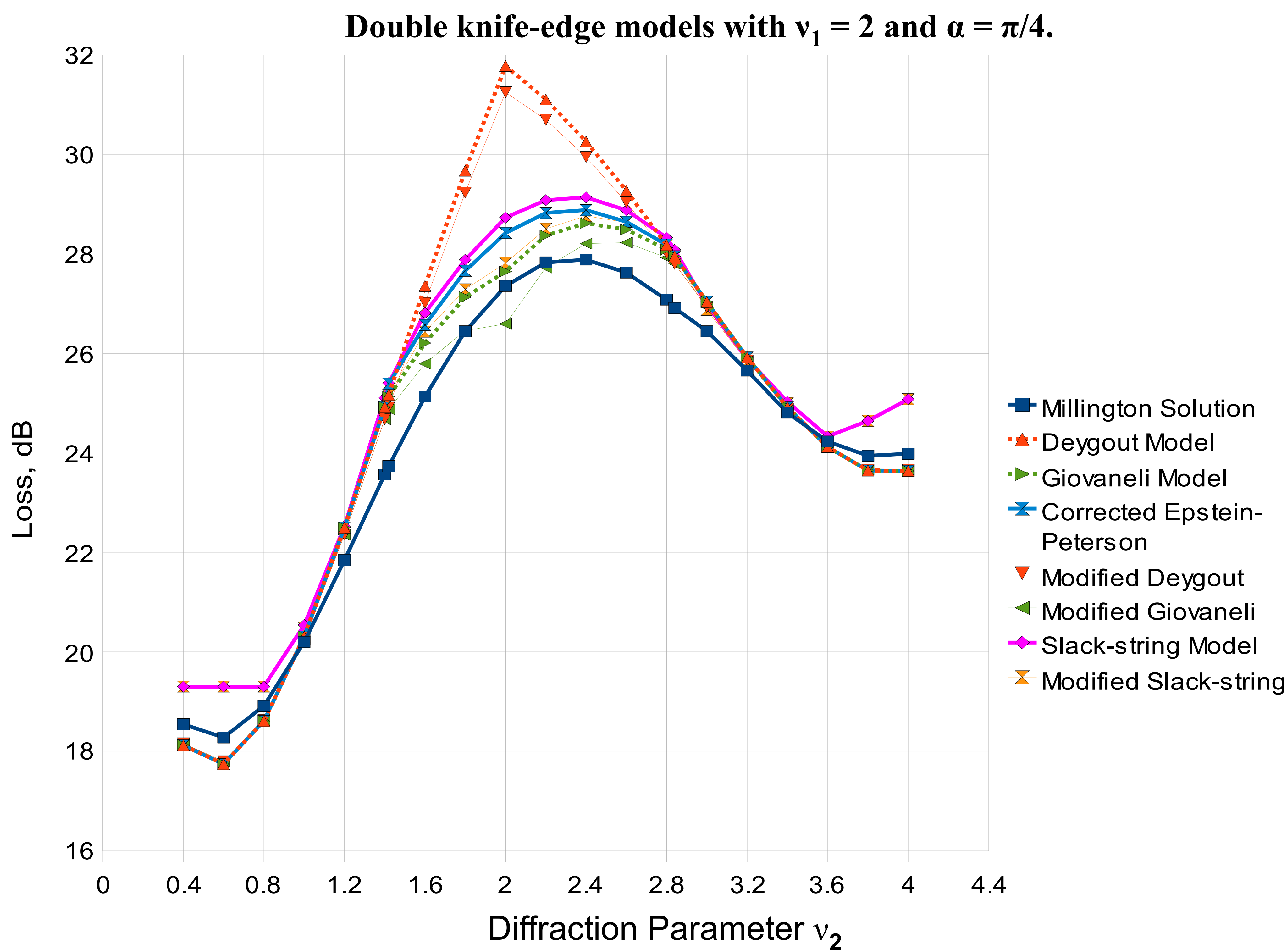
error, dB	Slack-string model	Deygout model	Giovaneli model
mean error	1.0	2.2	1.3
standard deviation	1.1	2.0	1.6
maximum	4.2	6.0	6.0
minimum	-1.6	-0.5	-0.5

A number of examples to follow ...

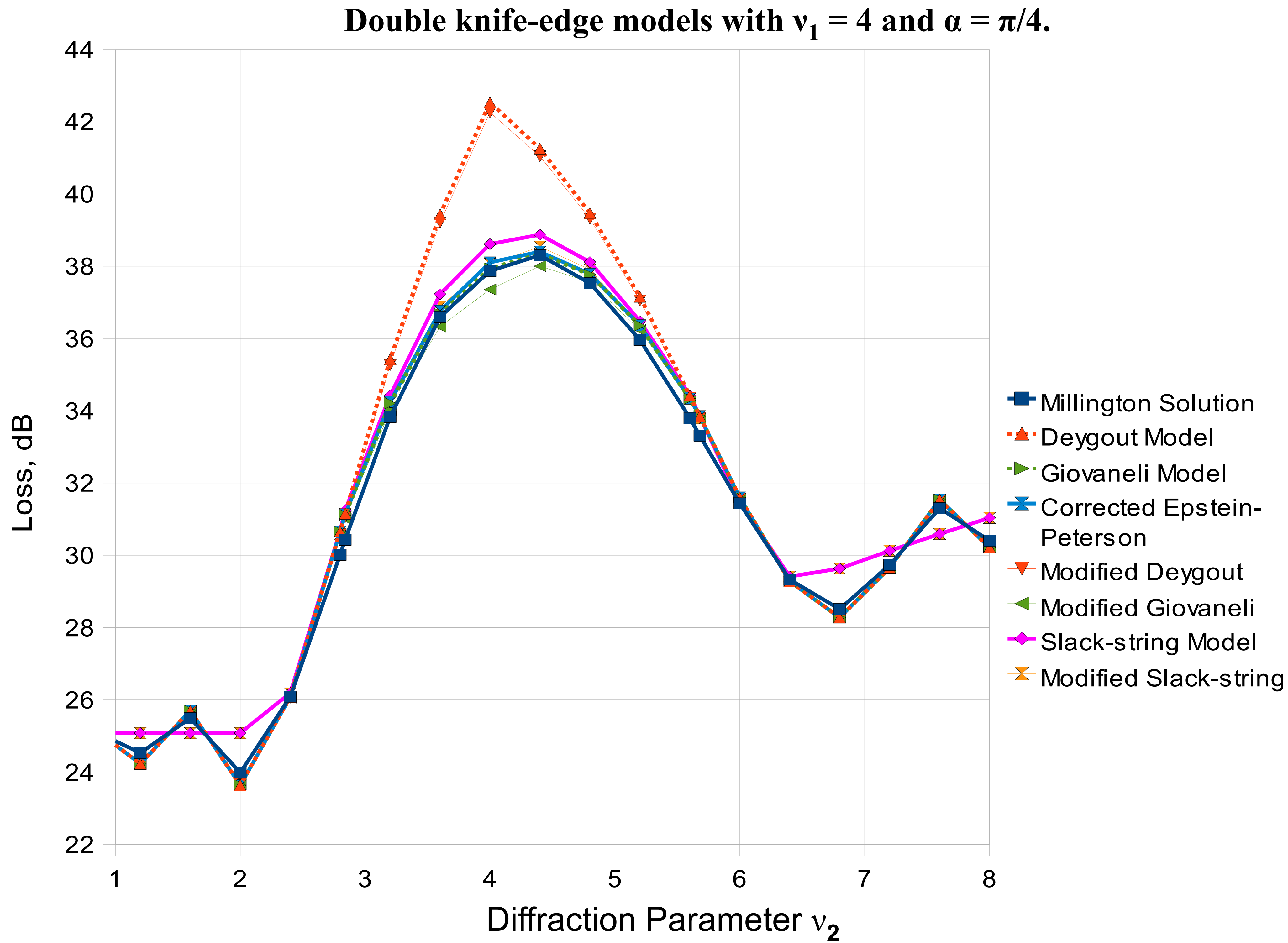


Double knife-edge models with ν1 = 0.5 and α = π/4.
Loss, dB
Diffraction Parameter ν2
20
19
18
17
16
15
14
13
12
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Millington Solution
Deygout Model
Giovaneli Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string


Double knife-edge models with ν1 = 1 and α = π/4.
Loss, dB
24
22
20
18
16
14
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Diffraction Parameter ν2
Millington Solution
Deygout Model
Giovaneli Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string



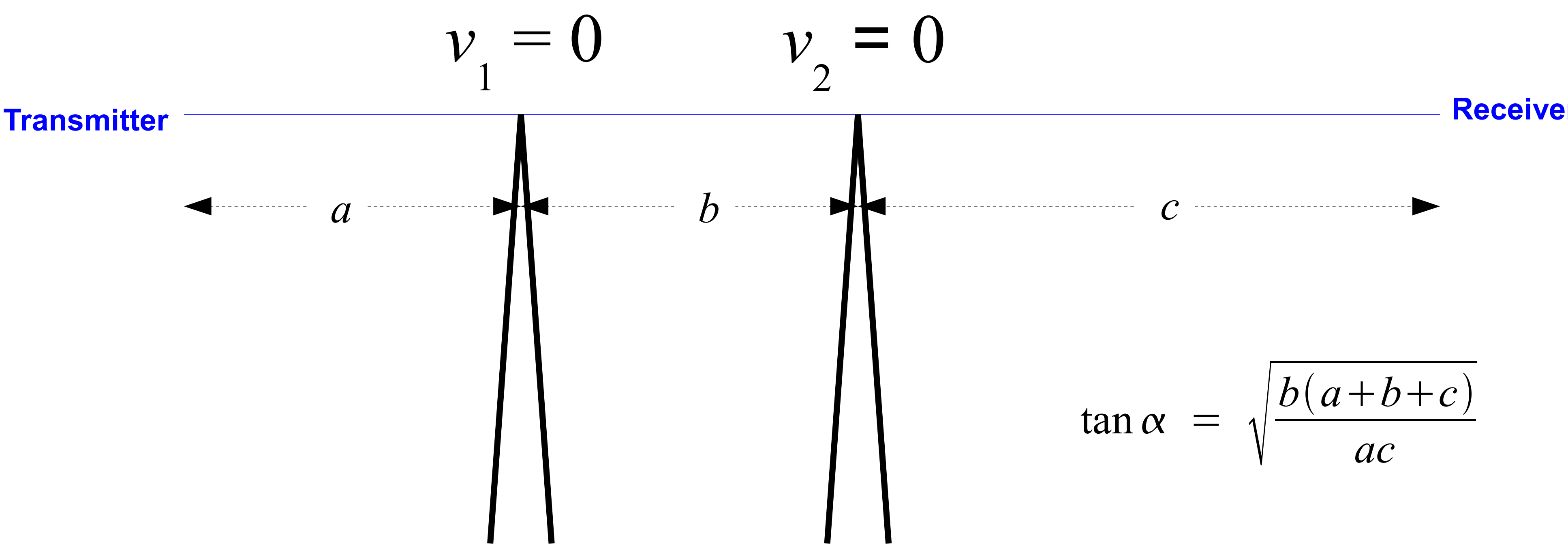
Double knife-edge models with $\nu_1 = 2$ and $\alpha = \pi/4$.
Loss, dB
Diffraction Parameter ν_2
32
30
28
26
24
22
20
18
16
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
Millington Solution
Deygout Model
Giovaneli Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string



Double knife-edge models with ν1 = 4 and α = π/4.
Loss, dB
Diffraction Parameter ν2
44
42
40
38
36
34
32
30
28
26
24
22
1
2
3
4
5
6
7
8
Millington Solution
Deygout Model
Giovaneli Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string

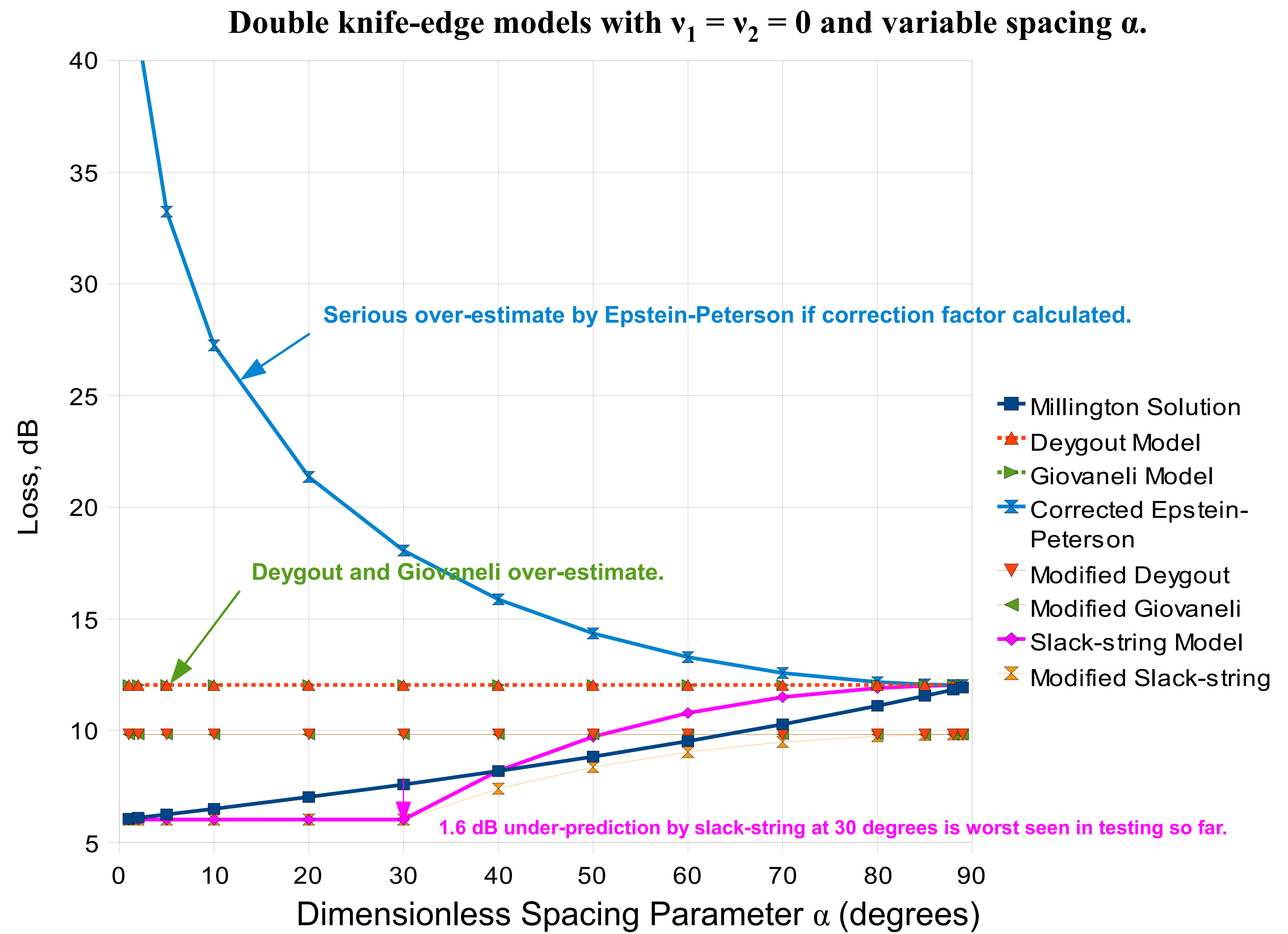
Testing with variable knife-edge spacing parameter α - two edges with Diffraction Parameter $v = 0$

Millington solution: L = -20.log(0.5 – α/2π) dB



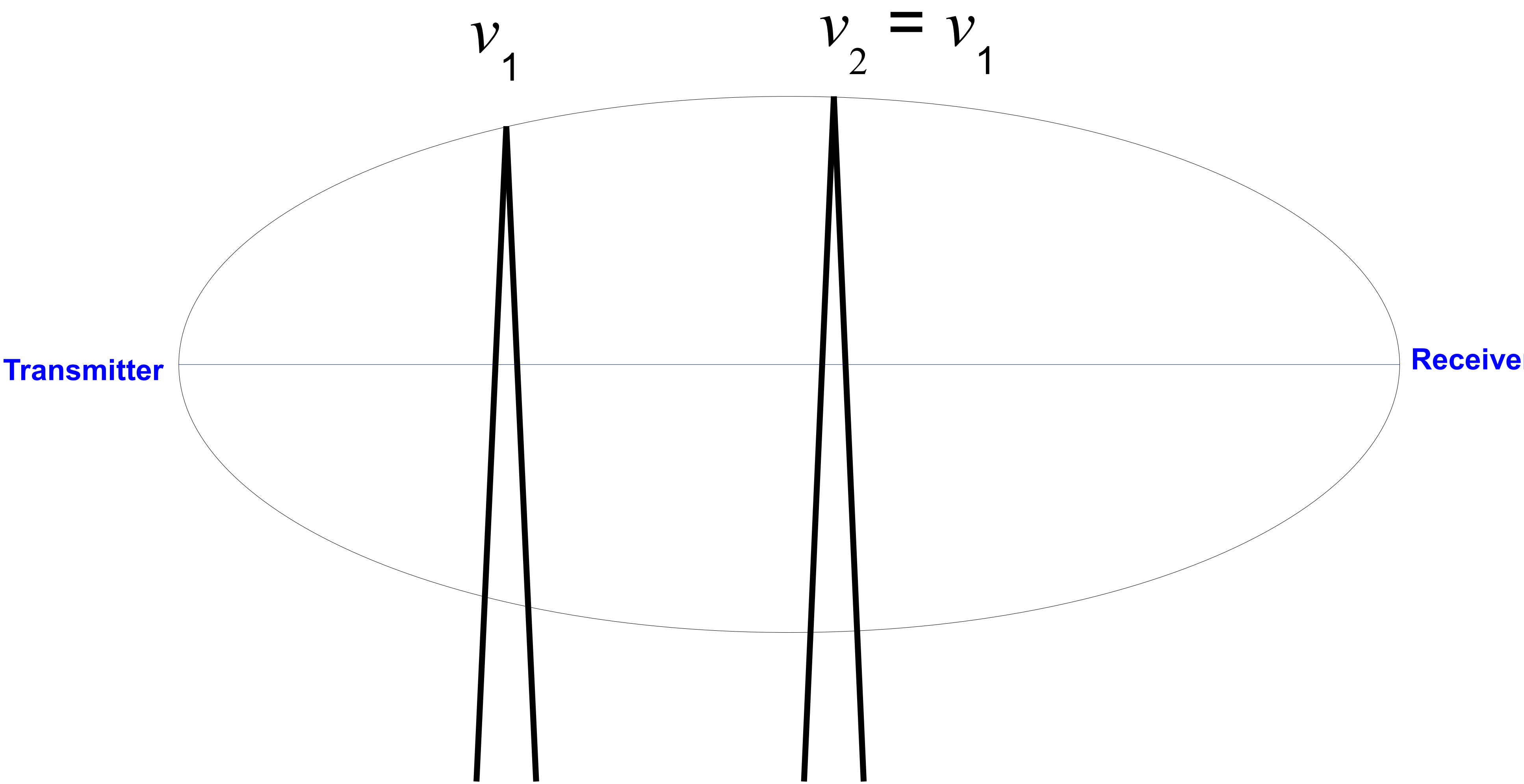
$$\tan\alpha = \sqrt{\frac{b(a+b+c)}{ac}}$$

Deygout and Giovaneli models over-estimate by up to 6 dB for small α (close edges).

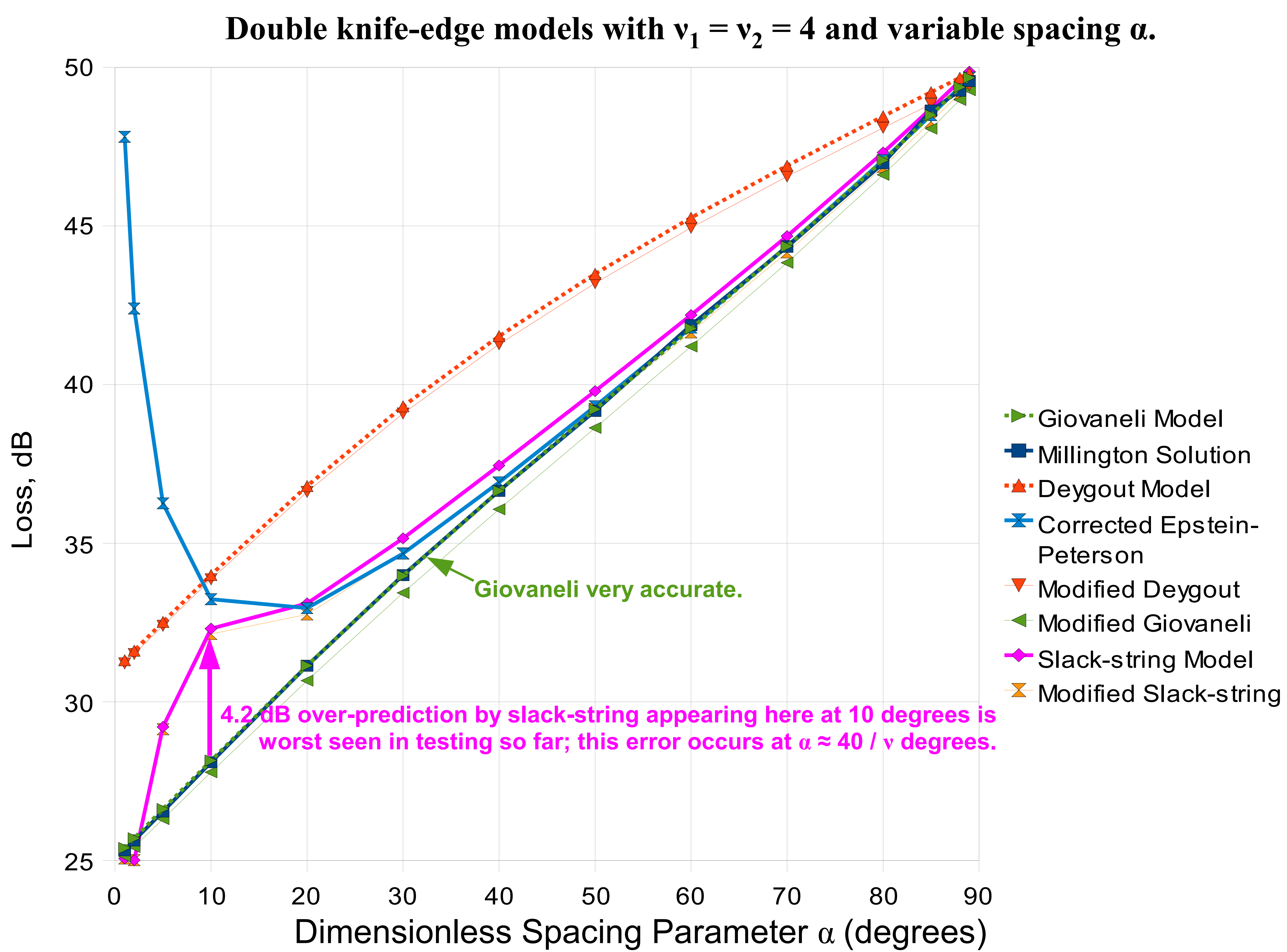


Double knife-edge models with ν1 = ν2 = 0 and variable spacing α.
Serious over-estimate by Epstein-Peterson if correction factor calculated.
Deygout and Giovaneli over-estimate.
1.6 dB under-prediction by slack-string at 30 degrees is worst seen in testing so far.
Loss, dB
Dimensionless Spacing Parameter α (degrees)
Millington Solution
Deygout Model
Giovaneli Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90

Testing with variable knife-edge spacing parameter α - two edges with equal Diffraction Parameter ν

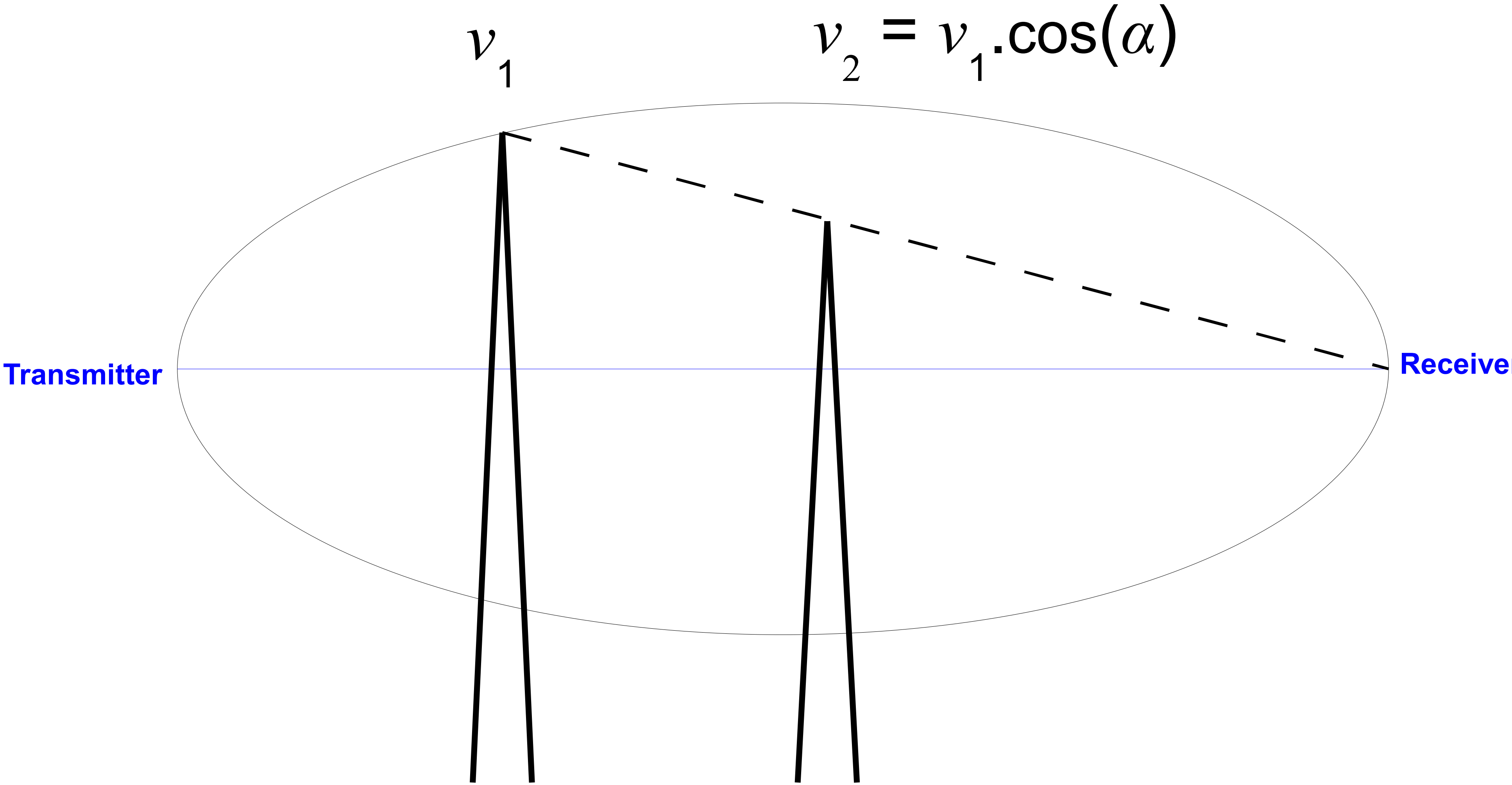


Giovaneli model is accurate for $\nu > 1$, but Deygout model over-estimates by up to 6 dB for close edges.

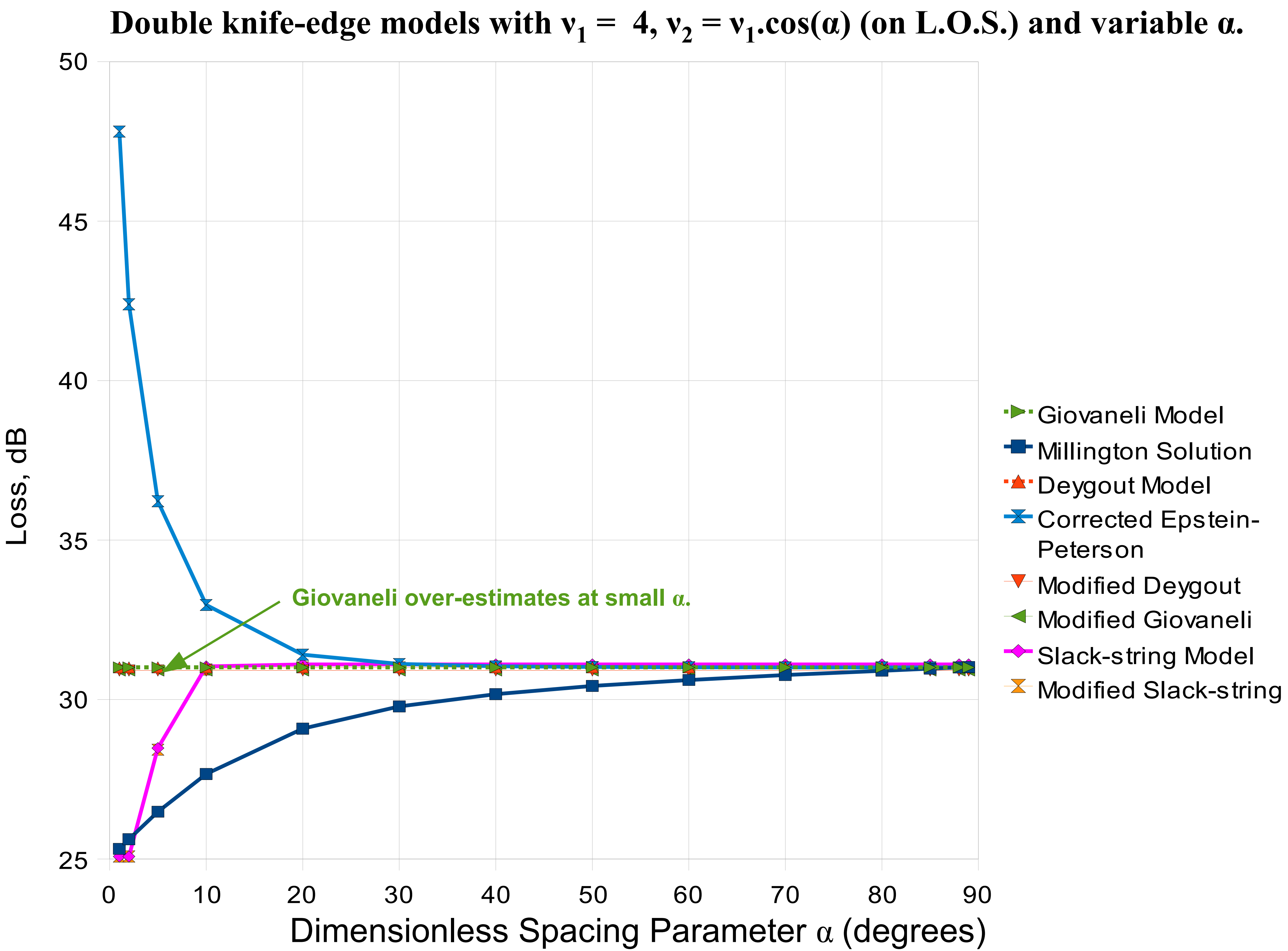


Double knife-edge models with ν1 = ν2 = 4 and variable spacing α.
Loss, dB
50
45
40
35
30
25
0
10
20
30
40
50
60
70
80
90
Dimensionless Spacing Parameter α (degrees)
Giovaneli very accurate.
4.2 dB over-prediction by slack-string appearing here at 10 degrees is
worst seen in testing so far; this error occurs at α ≈ 40 / ν degrees.
Giovaneli Model
Millington Solution
Deygout Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string

Testing with variable knife-edge spacing parameter α - two edges; second on Line-of-Sight of first.



Deygout and Giovaneli models over-estimate by up to 6 dB for small α (close edges).


Double knife-edge models with ν1 = 4, ν2 = ν1.cos(α) (on L.O.S.) and variable α.
Loss, dB
Dimensionless Spacing Parameter α (degrees)
Giovaneli over-estimates at small α.
Giovaneli Model
Millington Solution
Deygout Model
Corrected Epstein-Peterson
Modified Deygout
Modified Giovaneli
Slack-string Model
Modified Slack-string
50
45
40
35
30
25
0
10
20
30
40
50
60
70
80
90

Multiple knife-edge models applied to real terrain - testing:

- 64 paths without tree-cover, with profiles from 1:50,000 and 1:100,000 topographic mapping.

Multiple knife-edge models applied to real terrain - testing:

- 64 paths without tree-cover, with profiles from 1:50,000 and 1:100,000 topographic mapping.
- 478 accurately calibrated measurements at heights ≥ 6 metres, frequency 150 ~ 1500 MHz.

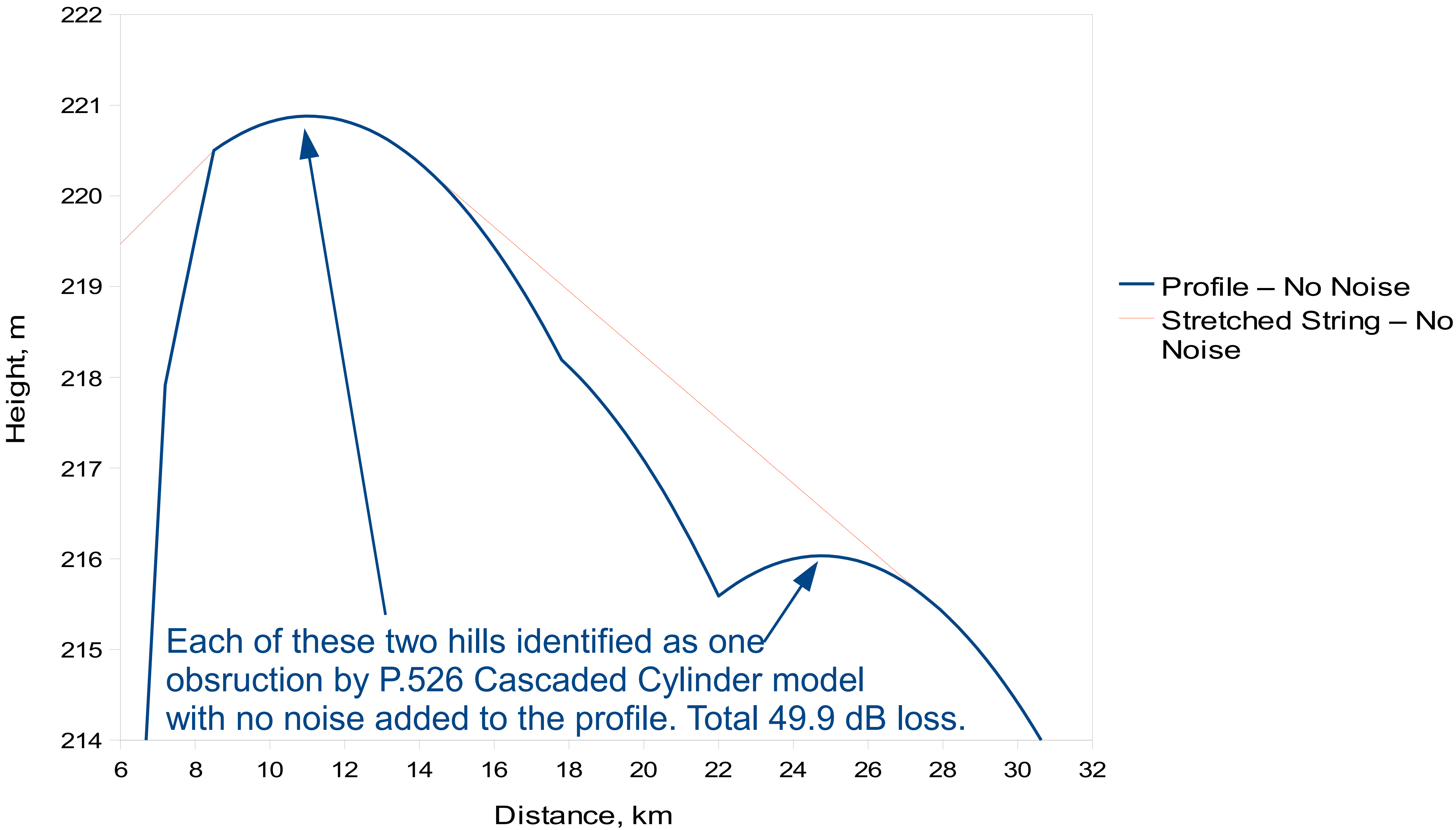
Multiple knife-edge models applied to real terrain - testing:

- 64 paths without tree-cover, with profiles from 1:50,000 and 1:100,000 topographic mapping.
- 478 accurately calibrated measurements at heights ≥ 6 metres, frequency 150 ~ 1500 MHz.
- Profile points interpolated to 0.25 km apart.

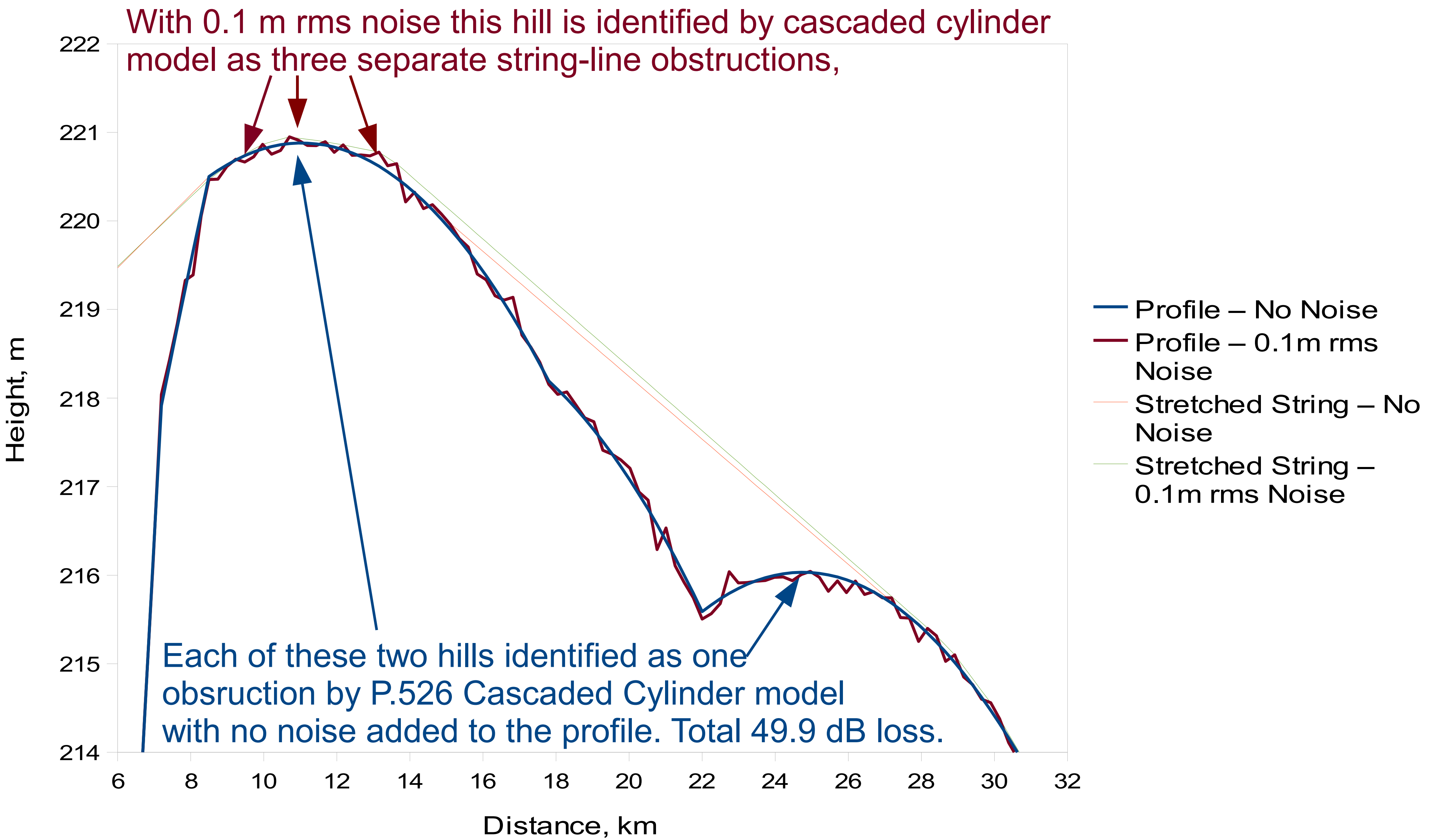
Multiple knife-edge models applied to real terrain - testing:

- 64 paths without tree-cover, with profiles from 1:50,000 and 1:100,000 topographic mapping.
- 478 accurately calibrated measurements at heights ≥ 6 metres, frequency 150 ~ 1500 MHz.
- Profile points interpolated to 0.25 km apart.
- Prediction model sensitivity to profile variation tested by finding the difference in the prediction when 0.1 m rms Gaussian noise is added to the interpolated profile points.

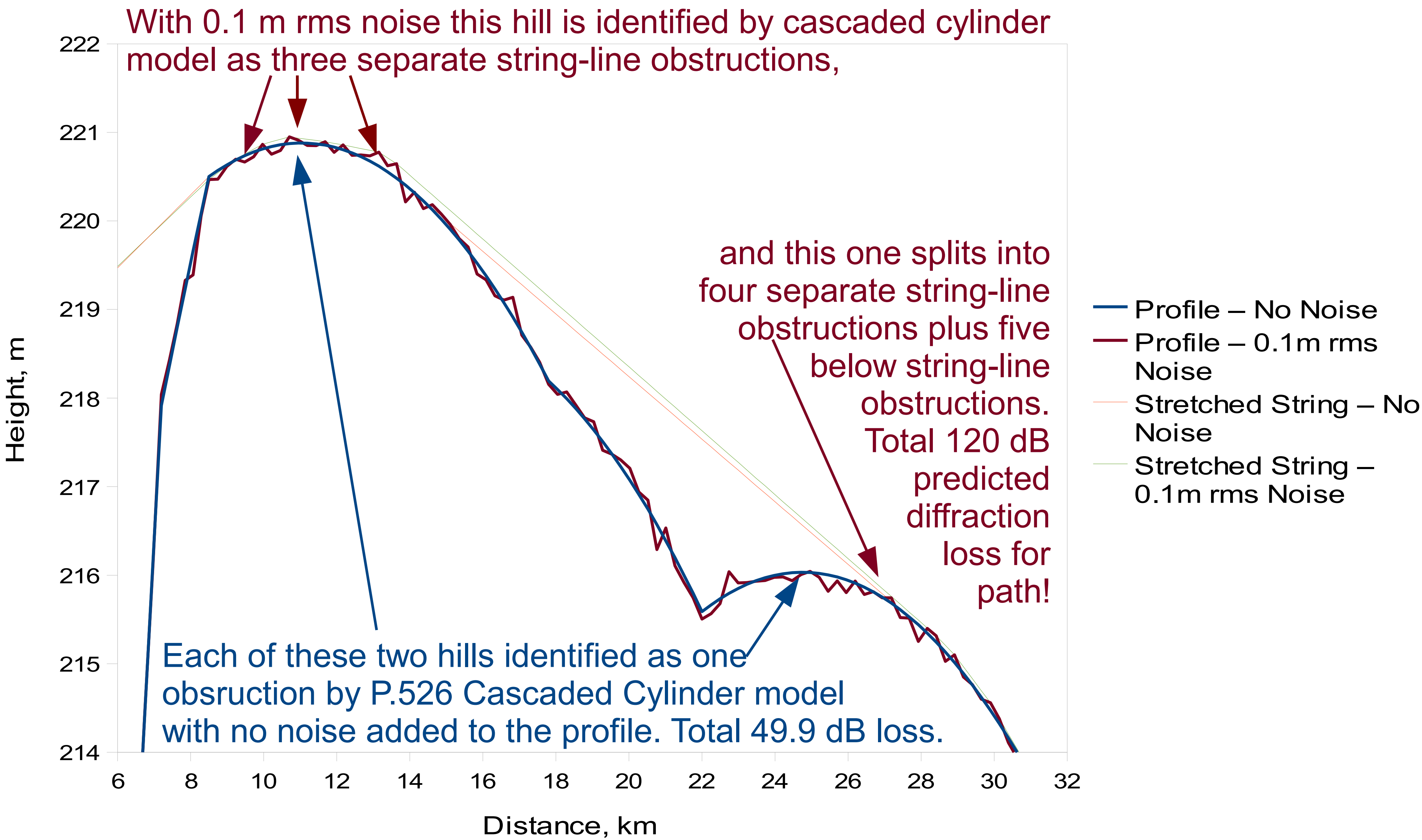
Noise Addition Technique – an example from the dataset



Noise Addition Technique – an example from the dataset



Noise Addition Technique – an example from the dataset



Multiple knife-edge models applied to real terrain - options:

- Treat each profile point as a knife-edge
  - overprediction can be prevented by: limiting analysis to N most significant edges; or "modified" models with multipliers < 1 for subsequent edges.

Testing against Measurements – models treating all profile points as separate obstructions

Multiple knife-edge model	Correlation of measured loss with predicted	Prediction Error (dB): Mean	Prediction Error (dB): Std. Dev.	Difference (dB) with 0.1 m rms noise: Mean	Difference (dB) with 0.1 m rms noise: Std. Dev.
P.526 Cascaded knife-edge	0.785	0.3	7.2	0.03	0.18
Deygout 5 worst edges	0.855	0.4	6.3	0.06	0.22
Giovaneli 5 worst edges	0.846	-0.2	6.2	0.04	0.24
Modified Deygout all points	0.858	0.8	9.1	0.01	1.01
Modified Giovaneli all points	0.861	-0.2	8.0	-0.02	1.22
Slack String all points	0.902	-5.3	5.4	0.03	0.16
Modified Slack String all points	0.832	-8.5	6.2	0.02	0.12

"Modified" models: (to avoid excessive calculated loss when all profile points included)

$$L(v) = J(v).\left[1 - \exp\left(-\,{}^{L_{left}}\!/_{6}\right)\right].\left[1 - \exp\left(-\,{}^{L_{right}}\!/_{6}\right)\right]$$

L_{left}, L_{right} are the $L(v)$ previously calculated for the current sub-path endpoints (∞ if a terminal)

Multiple knife-edge models applied to real terrain - options:

- Treat each profile point as a knife-edge
  - overprediction can be prevented by: limiting analysis to N most significant edges; or “modified” models with multipliers < 1 for subsequent edges.

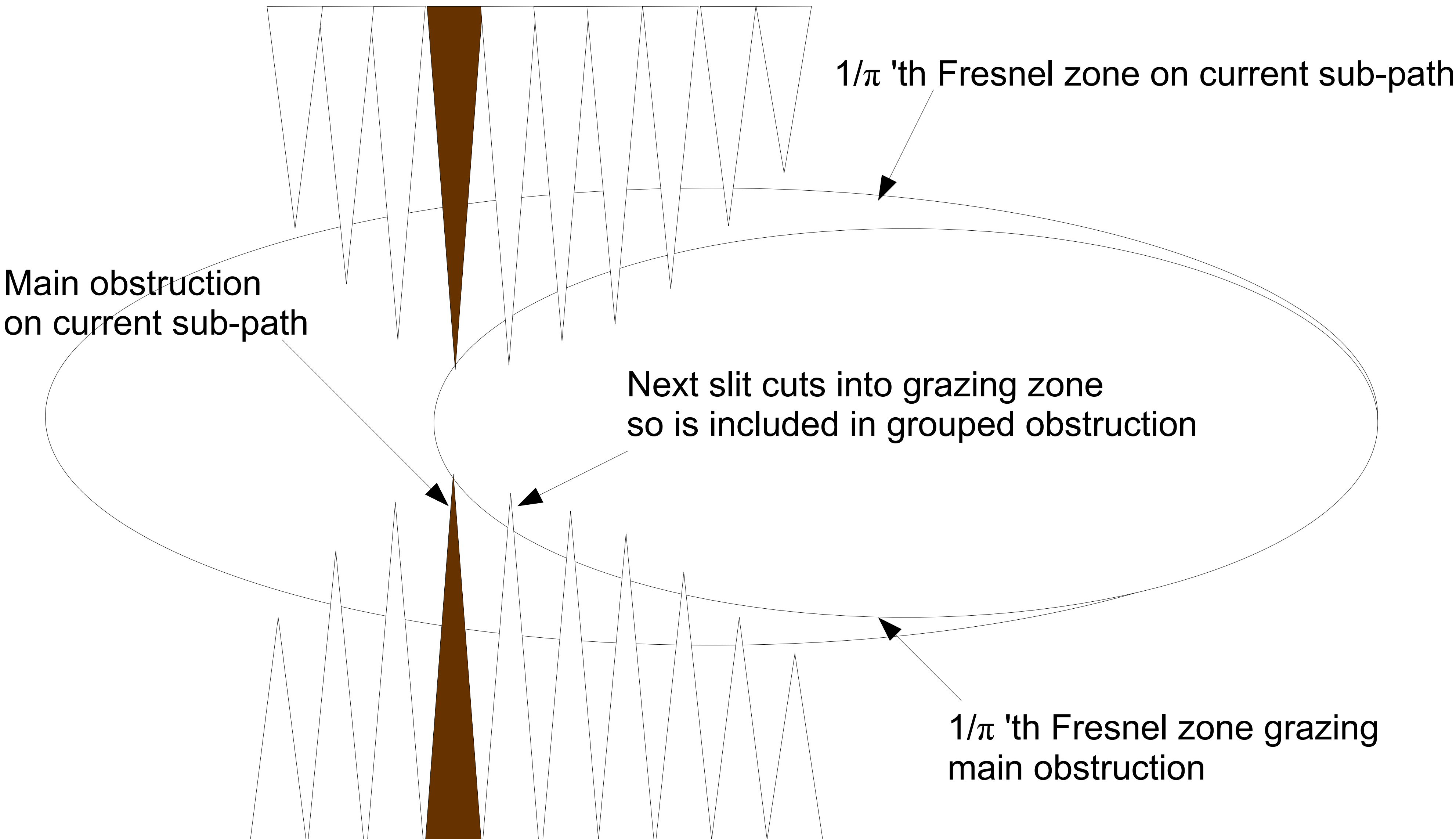
Multiple knife-edge models applied to real terrain - options:

- Treat each profile point as a knife-edge
  – overprediction can be prevented by: limiting analysis to N most significant edges; or “modified” models with multipliers < 1 for subsequent edges.
- Group adjacent obstruction points together to form a single non knife-edge obstruction
  – for example Rec. ITU-R P.526 Cascaded Cylinder model.

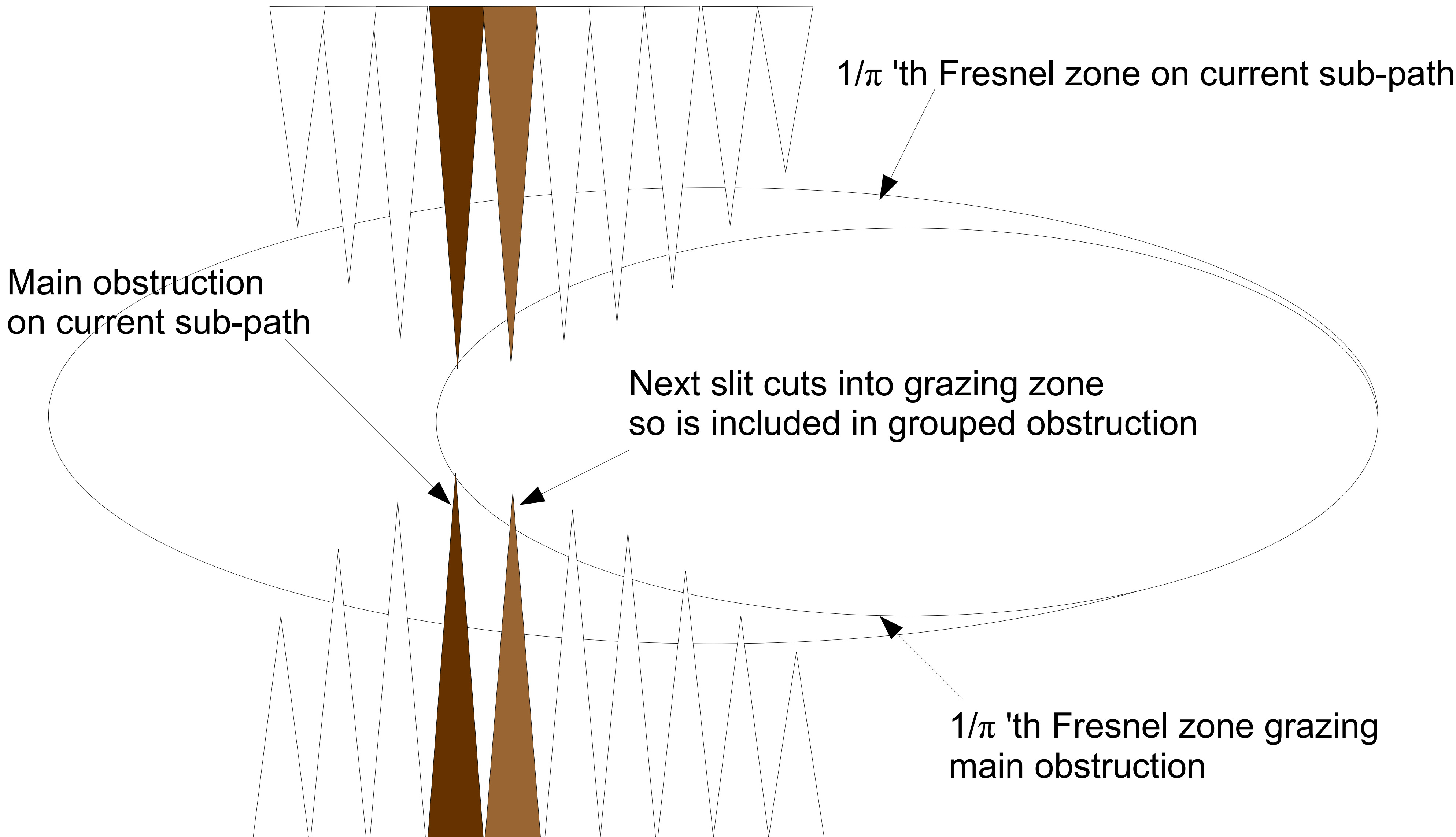
Multiple knife-edge models applied to real terrain - options:

- Treat each profile point as a knife-edge
  - overprediction can be prevented by: limiting analysis to N most significant edges; or “modified” models with multipliers < 1 for subsequent edges.
- Group adjacent obstruction points together to form a single non knife-edge obstruction
  - for example Rec. ITU-R P.526 Cascaded Cylinder model.
  - or a Slack-String grouped obstruction model...

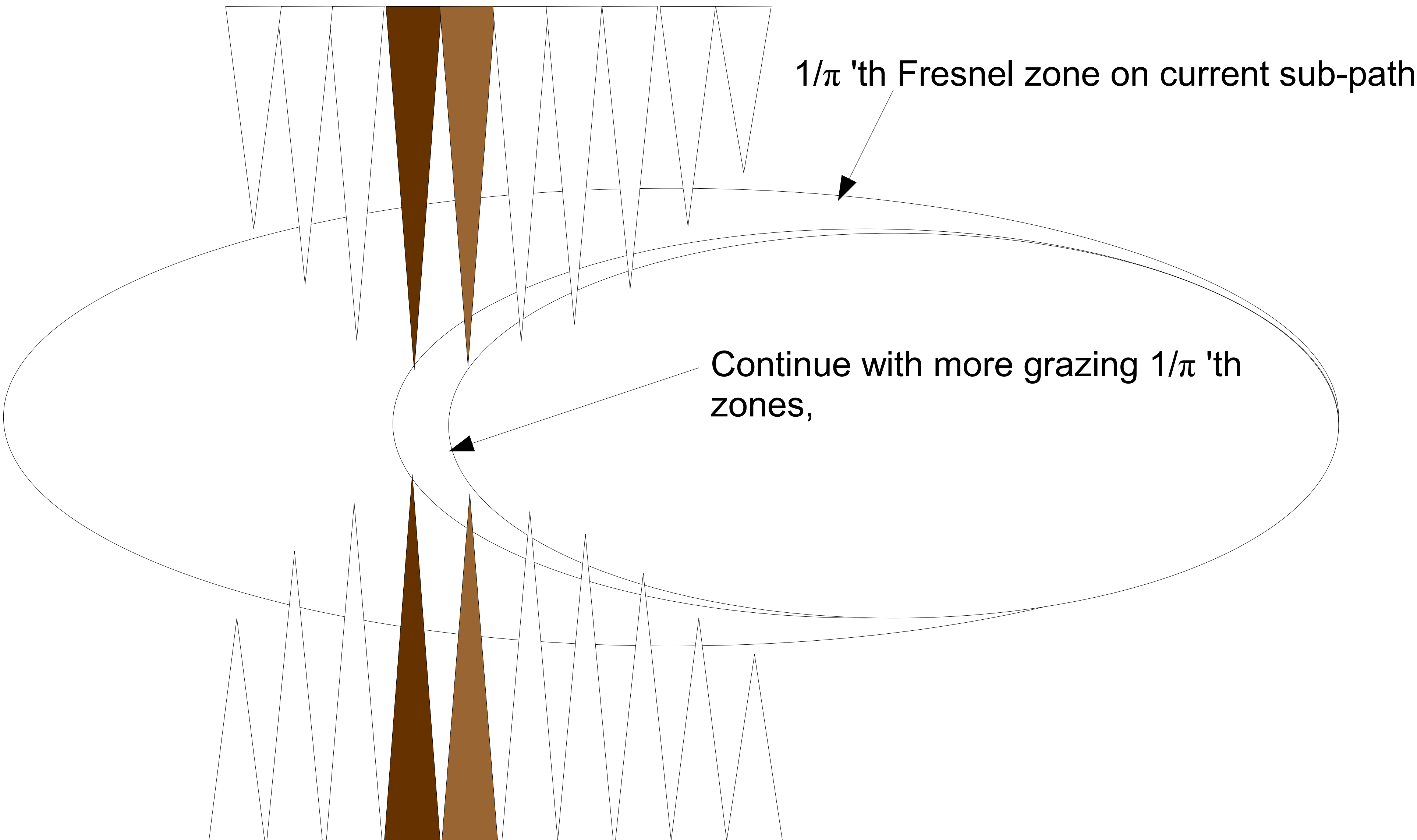
Grouping adjacent slack-string slits into combined obstructions – one possible empirical approach



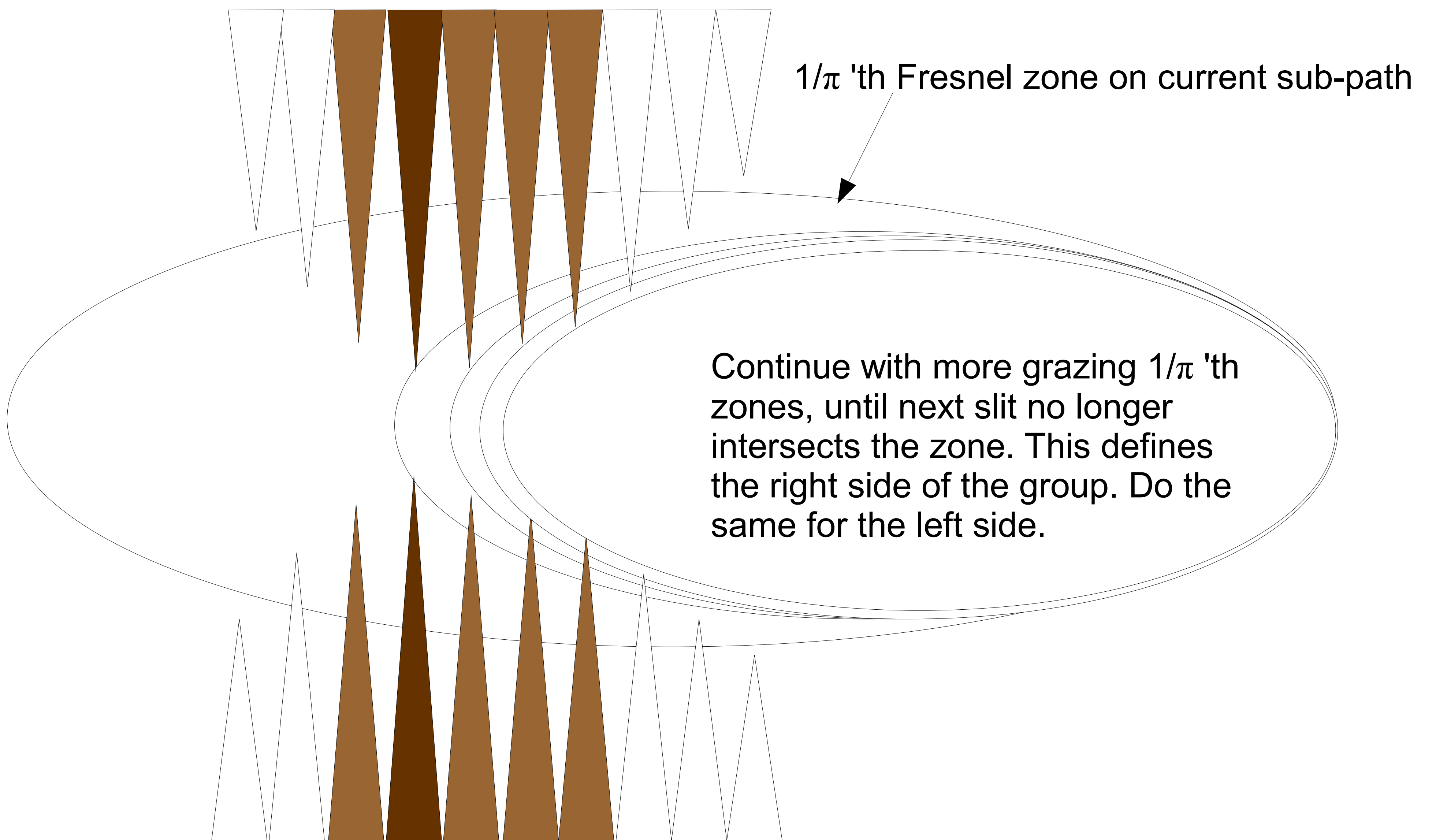
Grouping adjacent slack-string slits into combined obstructions – one possible empirical approach



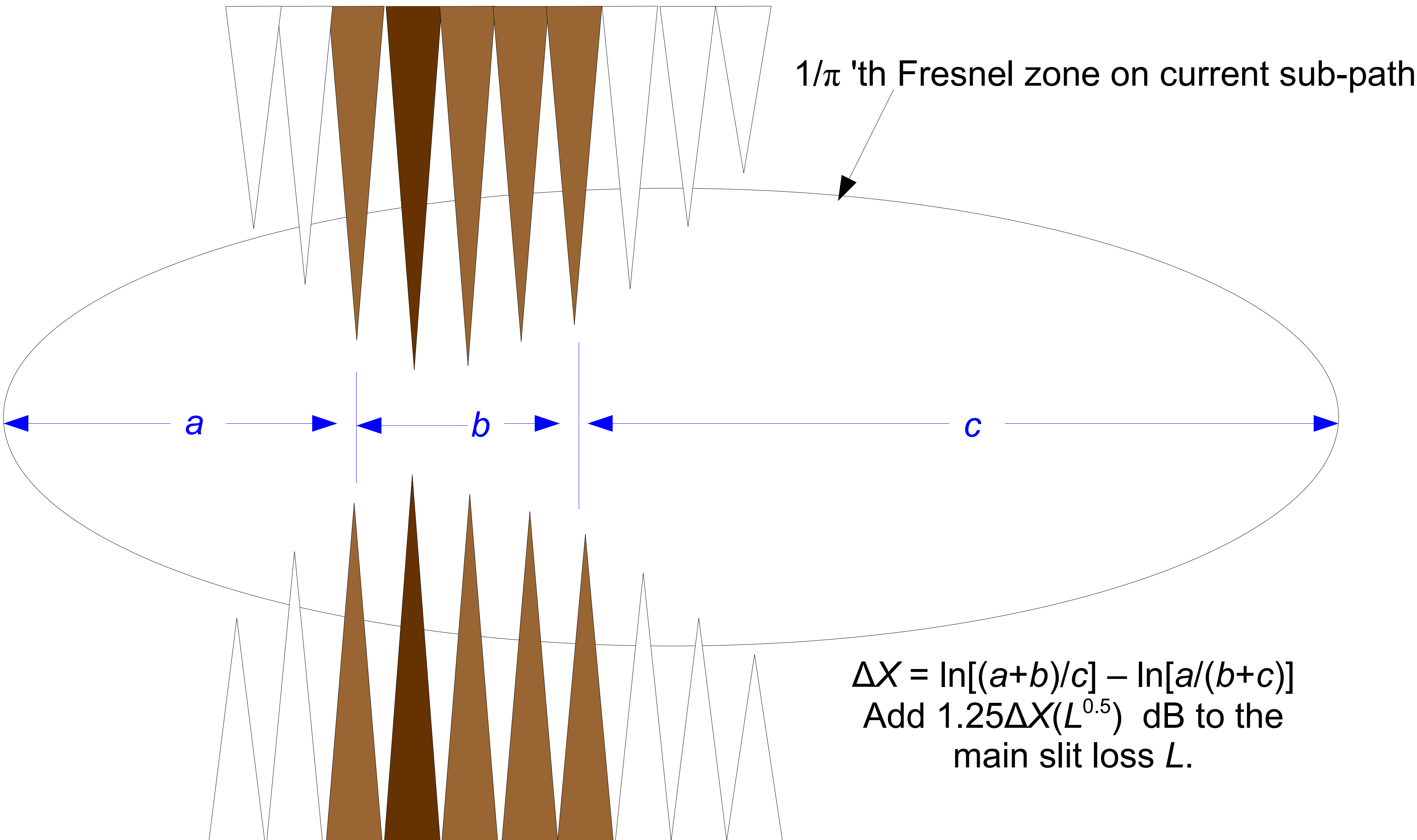
Grouping adjacent slack-string slits into combined obstructions – one possible empirical approach



Grouping adjacent slack-string slits into combined obstructions – one possible empirical approach



Grouping adjacent slack-string slits into combined obstructions – one possible empirical approach



$\Delta X = \ln[(a+b)/c] - \ln[a/(b+c)]$

Add $1.25\Delta X(L^{0.5})$ dB to the main slit loss L.

Testing against Measurements – models grouping adjacent profile points together

Cascaded cylinder model – multiple knife-edge model used	Correlation of measured loss with predicted	Prediction Error (dB):		Difference (dB) with 0.1 m rms noise	
		Mean	Std. Dev.	Mean	Std. Dev.
Corrected Epstein-Peterson (P.526)	0.838	-2.9	9.8	3.88	15.72
Giovaneli	0.832	-3.6	9.4	2.63	9.56
Slack String	0.857	-3.1	8.6	0.44	2.03

Slack String model with points grouped according to (1/pi)'th Fresnel zone intercept grazing previous slit	Correlation of measured loss with predicted	Prediction Error (dB):		Difference (dB) with 0.1 m rms noise	
		Mean	Std. Dev.	Mean	Std. Dev.
add 1.25dX(L^0.5) to main slit loss L	0.931	-0.6	4.9	-0.10	0.69

This grouped slack-string model appears to have generally reasonable accuracy for plane-Earth paths as well as the above irregular paths, but can under-estimate the loss of smooth spherical Earth paths. Further work is needed, but the concept offers promise as a way of grouping adjacent obstruction points for good accuracy, with low sensitivity to added noise on the path profile. [see next slide for all results presented together]

All profile points as separate obstructions:

Multiple knife-edge model	Correlation of measured loss with predicted	Prediction Error (dB): Mean	Prediction Error (dB): Std. Dev.	Difference (dB) with 0.1 m rms noise: Mean	Difference (dB) with 0.1 m rms noise: Std. Dev.
P.526 Cascaded knife-edge	0.785	0.3	7.2	0.03	0.18
Deygout 5 worst edges	0.855	0.4	6.3	0.06	0.22
Giovaneli 5 worst edges	0.846	-0.2	6.2	0.04	0.24
Modified Deygout all points	0.858	0.8	9.1	0.01	1.01
Modified Giovaneli all points	0.861	-0.2	8.0	-0.02	1.22
Slack String all points	0.902	-5.3	5.4	0.03	0.16
Modified Slack String all points	0.832	-8.5	6.2	0.02	0.12

Adjacent profile points grouped into obstructions:

Cascaded cylinder model – multiple knife-edge model used	Correlation of measured loss with predicted	Prediction Error (dB): Mean	Prediction Error (dB): Std. Dev.	Difference (dB) with 0.1 m rms noise: Mean	Difference (dB) with 0.1 m rms noise: Std. Dev.
Corrected Epstein-Peterson (P.526)	0.838	-2.9	9.8	3.88	15.72
Giovaneli	0.832	-3.6	9.4	2.63	9.56
Slack String	0.857	-3.1	8.6	0.44	2.03

Slack String model with points grouped according to (1/pi)'th Fresnel zone intercept grazing previous slit	Correlation of measured loss with predicted	Prediction Error (dB): Mean	Prediction Error (dB): Std. Dev.	Difference (dB) with 0.1 m rms noise: Mean	Difference (dB) with 0.1 m rms noise: Std. Dev.
add 1.25dX(L^0.5) to main slit loss L	0.931	-0.6	4.9	-0.10	0.69

Concusions

- The P.526 cascaded knife-edge model was found to have good accuracy and low sensitivity to added profile noise for the paths studied.
- Some models (e.g. P.526 cascaded cylinder) can be very severely affected by profile noise.
- A new model, the “slack-string” model, offers low sensitivity to profile noise and good accuracy, although it is computationally more intensive on some paths than the Deygout or Giovaneli multiple knife-edge models.